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A Proposed Solution to the Longitudinal Instabilities of the Ball-Bartoe Jetwing Through the Addition of a Thin, Fixed Slat to the Horizontal Tail

Steven L. Sisterman
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To the Graduate Council:

I am submitting herewith a thesis written by Steven L. Sisterman entitled "A Proposed Solution to the Longitudinal Instabilities of the Ball-Bartoe Jetwing Through the Addition of a Thin, Fixed Slat to the Horizontal Tail." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

Roger A. Crawford, Major Professor

We have read this thesis and recommend its acceptance:

Ralph D. Kimberlin, A. D. Vakih

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A PROPOSED SOLUTION TO THE LONGITUDINAL INSTABILITIES OF THE BALL-BARTOE JETWING THROUGH THE ADDITION OF A THIN, FIXED SLAT TO THE HORIZONTAL TAIL

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Steven L. Sisterman

May 1989

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ABSTRACT

The Ball-Bartoe Jetwing research aircraft was developed as a STOL demonstrator vehicle employing single engine powered lift by means of upper surface blowing. Unfortunately, the aircraft has been plagued by longitudinal instabilities since the first flight. These instabilities have prevented an exploration of the full STOL potential of the aircraft since the problem becomes more severe during low airspeed flight.

A review of the historical data indicated that the instabilities may be attributed to the downwash flow that blanketed the horizontal tail in certain flight conditions. As the blown flaps were deflected to increase lift at low airspeeds, the resulting downwash inhibited the tail effectiveness and eventually caused the tail to stall. The small planform area and relatively thin NACA 0008 airfoil of the horizontal tail have been identified as contributing factors in the instability problem.

An evaluation of the current applications of high lift devices determined that the thin, fixed slat was the most appropriate solution for the insufficiencies of the horizontal tail. The design of the slat was optimized to simplify fabrication and installation. The projected results indicate that the slat should provide some measure of stall resistance and increase the tail effectiveness.

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LIST OF SYMBOLS AND ABBREVIATIONS

Cj	two-dimensional section blowing coefficient
Cl	two-dimensional section lift coefficient
CL	three-dimensional lift coefficient
CLmax	maximum lift coefficient
Hpi	indicated pressure altitude
iT	incidence angle of horizontal tail with respect to fuselage axis
OAT	outside air temperature
Rtr	true Reynolds number
Vi	indicated airspeed
Vtr	true airspeed
α	aircraft angle of attack
αT	horizontal tail angle of attack
δe	elevator deflection angle with respect to chord line, positive for trailing edge down
εerr	difference between calculated and measured downwash angles
εT	wing-induced downwash angle at the aerodynamic center of the horizontal tail
ρ	air density

1. INTRODUCTION

1.1. History of the Ball-Bartoe Jetwing

The Ball-Bartoe Jetwing was created to demonstrate the employment of a single jet engine to provide an aircraft with powered lift by means of upper wing surface blowing. This adaptation of a powered lift technique originated with Mr. O. E. Bartoe while he was acting as the Vice-President and General Manager of Ball Brothers Research, a division of the Ball Corporation. The single engine design of the Jetwing was a departure from previous applications of upper surface blowing, all of which were based upon multiple engine configurations. The Ball-Bartoe Aircraft Company was organized to further develop the original theory and to design and build an aircraft which would prove the viability of the concept.

The development of the Jetwing research aircraft was begun in 1973. The final design of the proposed aircraft included a narrow rectangular nozzle which directed both the bypass and core exhaust of the single turbofan engine over approximately 70% of the wing span. The resulting aircraft was a relatively inexpensive test vehicle for determining the flight characteristics of the single-engine, powered lift concept. The construction of the aircraft was completed in December, 1976, and the Jetwing was readied for a series of wind tunnel and flight tests.

The full-scale tests in the NASA Ames Research Center 40' x 80' wind tunnel first revealed a defect in the design of the aircraft. The Jetwing was found to be neutrally stable in the longitudinal plane, under optimum conditions, but would quickly become unstable. To counter this flaw, the designers placed 300 pounds of lead ballast in the nose of the aircraft. After the first flight of the Jetwing in July, 1977, another 100 pounds of lead was added in an effort to improve the longitudinal stability. Initial flight tests also revealed that the horizontal tail had a tendency to stall when the aircraft was flown with a flap setting greater than 40 degrees at a velocity of 50 knots indicated airspeed. Flight testing of the Jetwing was continued with the additional safety constraint of a maximum flap deflection of 30 degrees at 50 knots indicated air-speed. In December, 1978, after the Ball-Bartoe Aircraft Company had completed the testing of the aircraft, the Jetwing was donated to the University of Tennessee.

Additional flight and ground test evaluations have been conducted by the University of Tennessee Space Institute (UTSI) Flight Operations, both independently and under contract with the Naval Air Systems Command. The results of these new tests confirmed the Short Takeoff and Landing (STOL) capabilities of the Jetwing, but the aircraft continued to be plagued with longitudinal stability problems which prevented an exploration of the full potential of the concept. These problems have been judged to be due to a flaw in the design of the research aircraft, rather than inherent to the concept of single engine powered lift.

The UTSI Flight Operations group were forced to restrict their inquiries into the very low speed corner of the Jetwing flight envelope for two reasons. First, during a flight test, the aircraft experienced a partial stall of the horizontal tail at 53 knots calibrated airspeed with a flap extension of 30 degrees, a condition that was within the previously determined safe flight limits of the aircraft. Second, the longitudinal instability of the aircraft was quite evident, even with smaller flap deflections, in flight conditions which combined low airspeed with high thrust. In the interest of safety, the investigations into the limits of the approach and departure capabilities were restricted. The redesign of the horizontal tail has been recommended on several occasions as a solution for both of these problems. The aircraft is now located in Tullahoma, Tennessee, where the UTSI Flight Operations continues to research the high lift capabilities of upper surface blowing.

1.2. Description of the Ball-Bartoe Jetwing

The Ball-Bartoe Jetwing is a STOL demonstrator aircraft which derives a high lift capability from the application of upper surface blowing. The general planform and layout of the aircraft is shown in Figure 1. The aircraft is powered

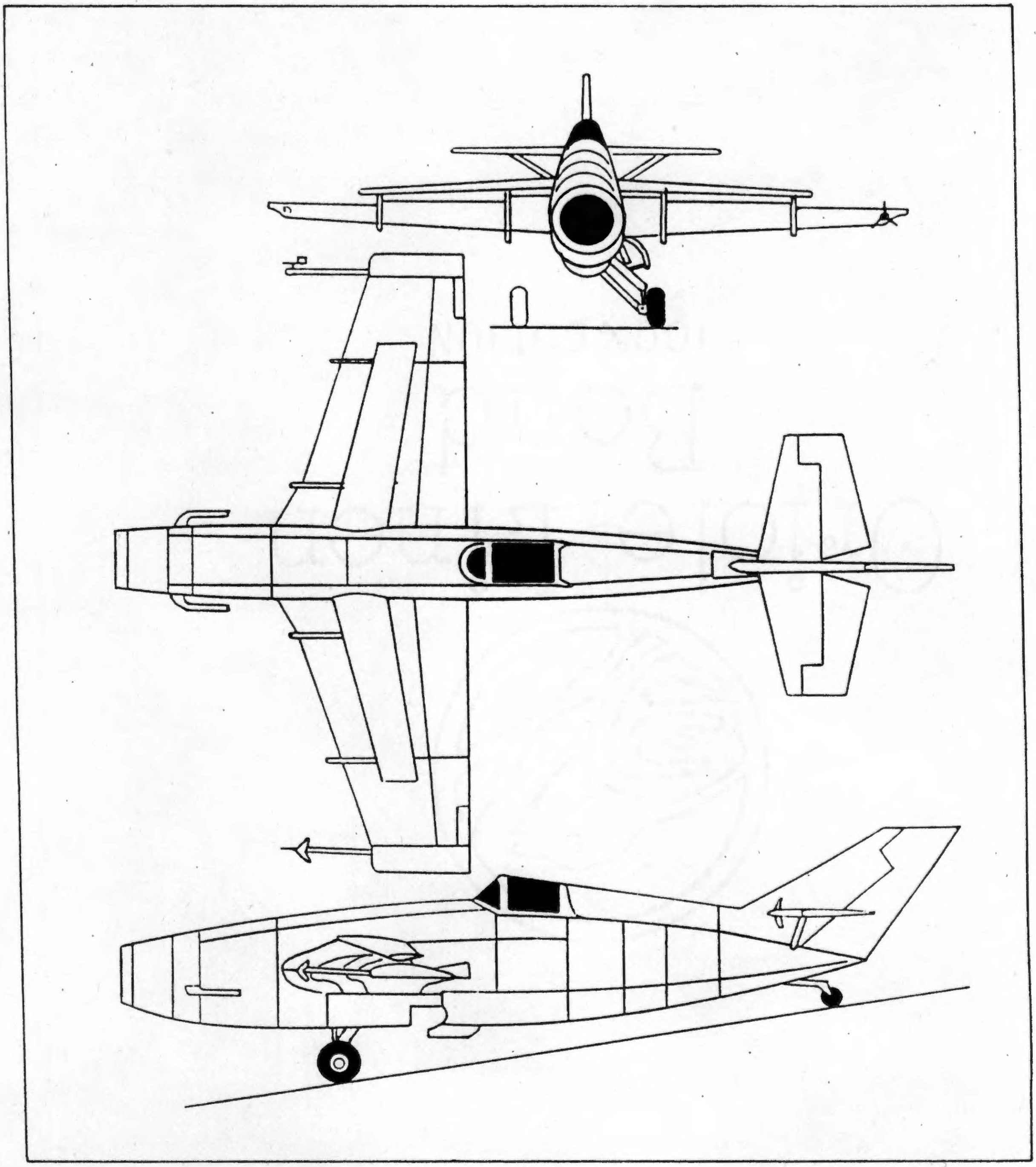


Figure 1. The Ball-Bartoe Jetwing

by a single Pratt and Whitney JT15D-1 turbofan engine which provides both the usual thrust component and the forced air flow over the wing and flap surfaces. The exhaust flow of the engine is entrained by a small wing surface above the rectangular nozzle and a Coanda single-element flap along the trailing edge of the wing. Summaries of the major dimensions and design characteristics of the Jetwing are provided in Tables 1, 2, and 3.

The current design plans for the horizontal tail plane call for a low aspect ratio, tapered planform with a NACA 0008 symmetrical airfoil section. The total area of the horizontal tail is 27.5 square feet. Of this total area, the horned elevator occupies 13.25 square feet. A planform view of the tail is shown in Figure 2. The thin airfoil section used in the construction of the horizontal tail and the relatively small tail volume of the aircraft have been the primary suspects in the search for a source of the longitudinal instabilities experienced in flight.

Table 1. Available Thrust for the Ball-Bartoe Jetwing at Sea Level, Standard Day Conditions

Powerplant: Pratt and Whitney JT15D-1 Turbofan

Condition	Thrust
Maximum Static Takeoff Thrust, Uninstalled	2200 lb
Maximum Static Continuous Thrust, Uninstalled	2050 lb
Maximum Static Continuous Thrust, Installed	1750 lb

Table 2. Weights and Capacities of the Ball-Bartoe Jetwing

Characteristic	Magnitude
Maximum Takeoff Weight	3750 lb
Empty Weight	2730 lb
Ballast	400 lb
Fuel Capacity, Weight	689 lb
Fuel Capacity, Volume	106 gal
Center of Gravity Location, Fully Loaded	35.5 %MAC

Table 3. Physical Description of the Ball-Bartoe Jetwing

Characteristic	Magnitude
Aircraft Geometry	
Length	28.60 ft
Height	6.10 ft
Wing Geometry	
Span	21.75 ft
Area	105.78 ft
Mean Aerodynamic Chord	5.08 ft
Aspect Ratio	4.48
Taper Ratio	0.46
Incidence Angle	0.0 deg
Airfoil Section at Root	Modified NACA 23020
Airfoil Section at Tip	NACA 23015
Upper Wing	
Span	15.10 ft
Area	23.16 ft
Airfoil Section	Clark Y, 12% thick
Incidence Angle to Wing	5.0 deg
Flap	
Span, Each	5.75 ft
Area, Each	10.60 ft
Deflection	0 to +55 deg
Horizontal Tail Geometry	
Span	9.33 ft
Area	27.50 ft
Mean Aerodynamic Chord	3.06 ft
Aspect Ratio	3.16
Taper Ratio	0.55
Incidence Angle, Trim Deflection	-2 to +20 deg
Airfoil Section	NACA 0008
Volume	0.74
Elevator	
Area	13.25 ft
Deflection	-25 to +29 deg
Vertical Tail Geometry	
Span	5.67 ft
Area	18.33 ft
Aspect Ratio	1.75
Volume	0.115
Airfoil Section	NACA 0008
Rudder	
Area	8.06 ft
Deflection	-20 to +20 deg

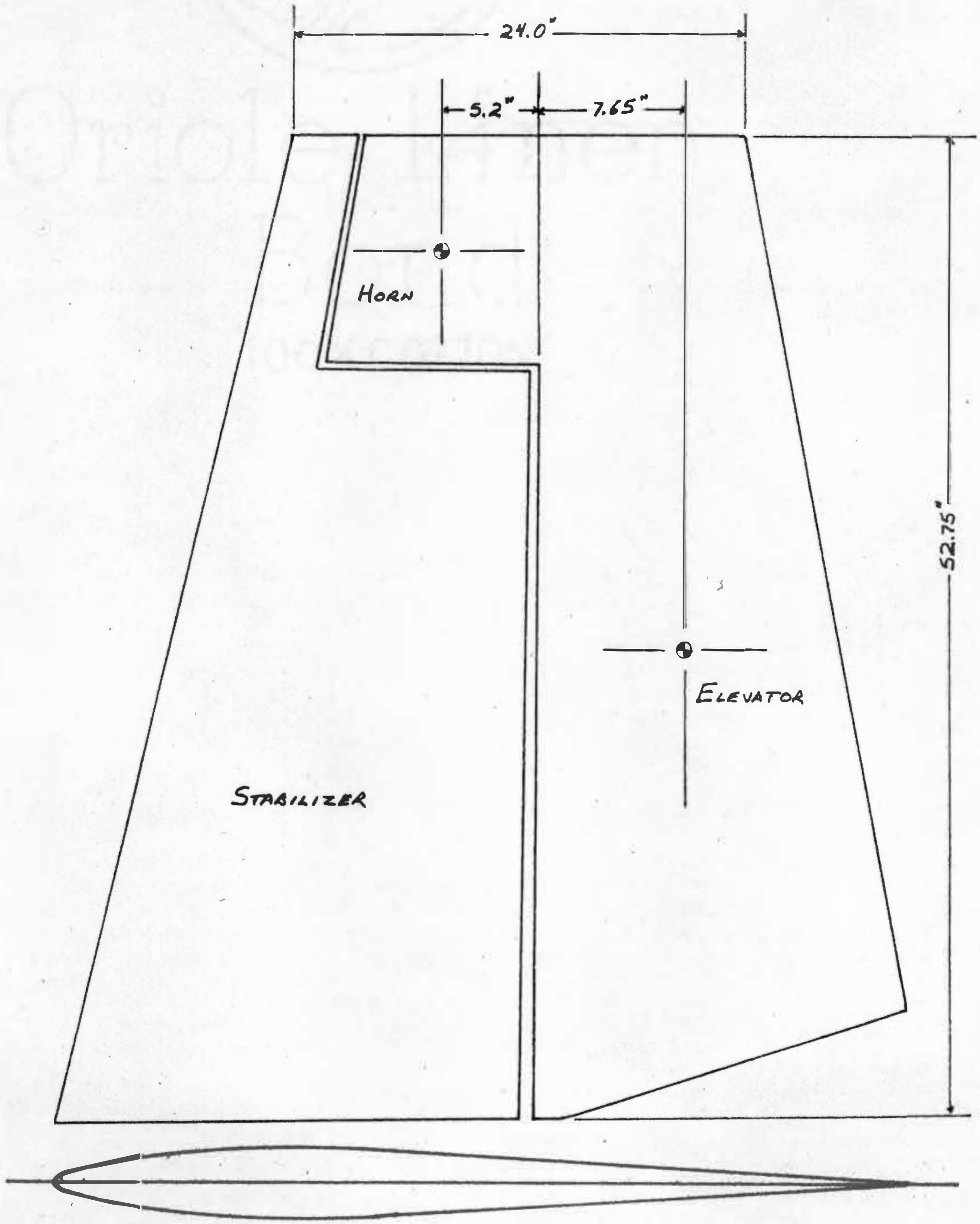


Figure 2. Planform View of the Horizontal Tail

2. PROBLEM STATEMENT

2.1. Results of the 1981 Flight Tests

The UTSI Flight Operations conducted flight and ground tests on the Ball-Bartoe Jetwing in 1981 under contract to the Naval Air Systems Command.[1] The purpose of the tests was to investigate the STOL capabilities and general handling characteristics of the Jetwing in order to determine the feasibility of applying the technology to future aircraft. The results of this series of flight tests reinforced the conclusions of the Ball-Bartoe Aircraft Company tests, finding that the Jetwing suffered from longitudinal instabilities in all flight configurations. This instability prevented the UTSI researchers from satisfactorily exploring the low speed performance of the Jetwing.

The occurrence of a tail stall within the assumed safe boundaries of the flight envelope, along with the discovery that the longitudinal instability increased under conditions of low airspeed and high thrust, forced the researchers to curtail their investigations into the STOL approach and departure limits of the aircraft. Kimberlin commented repeatedly on the instability problem in the report to the Naval Air Systems Command.

> Longitudinal control was more than adequate for all flight conditions except those at very low airspeed. . . . The problem is caused by the rather thin (8% thick) symmetrical horizontal tail section, which has a small leading edge radius, and the high downwash

> created by the deflected flaps and the upper surface blowing.
>
> The Jetwing exhibits a horizontal tail stall at very slow airspeeds with the flaps deflected. This objectional characteristic prohibits a complete evaluation of the low speed performance and handling qualities, but appears to be correctable by an improved horizontal tail design.
>
> The static and dynamic longitudinal stabilities of the Jetwing are negative for most of the configurations and centers of gravity tested. This instability appears correctable by proper location of the center of gravity, and the installation of a larger horizontal tail.

Since the location of the center of gravity is limited by the physical structure of the aircraft, a correction to the design of the horizontal tail appears to be the viable approach to reducing the longitudinal instabilities of the aircraft. The horizontal tail also appears to be the culprit when comparing the tail volume of the Jetwing to those of other aircraft which take advantage of powered lift. As shown in Table 4, the Jetwing tail volume is approximately half of the average value for the other aircraft, indicating that the planform area of the tail should probably be increased.

2.2. Results of the 1985 Flight Tests

The Ball-Bartoe Jetwing underwent another series of flight tests from September, 1983, to June, 1985, to further investigate the effects of upper surface blowing on the longitudinal stability of the aircraft.[2] The empirical

Table 4. Horizontal Tail Volume Comparisons of Powered Lift Aircraft

Aircraft	Tail Volume
Ball-Bartoe Jetwing	0.74
McDonnell Douglas YC-15	1.32
Boeing YC-14	1.60
NASA Quiet Shorthaul Research Aircraft	1.90

findings of the tests were combined with theoretical results, generated from a nonlinear vortex lattice theory, to produce an image of the flow field at the horizontal tail. The test results indicate that the flow near the tail is strongly influenced by the downwash created by the blown wing and flap. This problem has been a recognized characteristic of all aircraft employing blown flaps and often requires an all-moving tail to correct.[3] In addition, variations in engine thrust were found to have a direct effect on the longitudinal stability of the aircraft at low airspeeds. This limited amount of data forms the bulk of the investigations by the UTSI Flight Operations into the flow field about the horizontal tail of the Jetwing.

The data acquired in these tests were obtained by observing a tufted rake mounted perpendicularly to the tail plane at the leading edge of the horizontal tail. The tuft positions were recorded at each test condition by photographing the rake with a camera mounted near the vertical tail. The test conditions are presented in Table 5. The angle of attack of the aircraft that is listed was derived from wind tunnel data, since the sensors on the aircraft were deemed to have been influenced by distortions in the flow field. The data was then corrected to standard day conditions and the additional parameters were generated, as shown in Table 6. The blowing coefficient, Cj, was determined using a calibration of the engine thrust. The lift

Table 5. Test Conditions for the 1985 Flight Tests

No.	Flaps (deg)	Vi (kts)	Hpi (ft)	OAT (°F)	α (deg)	iT (deg)	δe (deg)
1	0	70	5400	52	18.2	2.80	-4.0
2		80	4260	52	14.0	2.80	-3.2
3		90	3350	65	11.5	1.50	-4.2
4		100	2400	69	9.5	2.05	-4.0
5	15	60	5500	59	18.0	1.75	-0.5
6		70	5100	60	12.0	1.75	-0.5
7		70	5400	59	12.5	2.05	-2.0
8		80	4700	63	10.0	1.95	-1.0
9		80	5800	58	9.0	1.80	-2.0
10		100	4300	65	4.5	2.05	-1.5
11	30	60	4500	50	12.0	2.98	0.7
12		70	6500	57	5.0	1.70	0.0
13		80	6250	57	2.0	1.80	0.0
14		90	4700	50	1.0	3.02	0.7
15	45	60	4300*	50	4.2	-0.90	2.0
16		70	4400**	50	-1.0	-0.15	1.2

* Descending flight path at 250 ft/min

** Descending flight path at 200 ft/min

Table 6. Reduced Data from the 1985 Flight Tests

No.	Flaps (deg)	Vtr (kts)	ρ (slg/ft^3)	Rtr (x10^6)	Cj	Cl	α (deg)	αT (deg)
1	0	76.49	.001993	2.03	.4282	2.0035	18.2	11.09
2		85.16	.002084	2.37	.3542	1.5519	14.0	11.82
3		93.77	.002096	2.62	.1961	1.1823	11.5	10.26
4		104.73	.002154	3.01	.1692	.9994	9.5	9.33
5	15	67.10	.001950	1.75	.7157	2.6067	18.0	2.75
6		77.71	.001986	2.06	.5264	1.9194	12.0	2.30
7		78.14	.001964	2.05	.4940	1.8869	12.5	4.01
8		87.78	.002001	2.34	.3569	1.4974	10.0	3.85
9		89.16	.001940	2.31	.3819	1.4634	9.0	2.39
10		108.99	.002023	2.94	.2497	.9688	4.5	1.29
11	30	64.55	.002072	1.79	.9406	2.6703	12.0	1.41
12		78.34	.001912	2.00	.5763	1.8970	5.0	-5.31
13		91.48	.001912	2.33	.4226	1.3942	2.0	-5.39
14		97.79	.002061	2.69	.3687	1.1649	1.0	-4.04
15	45	64.38	.002084	1.79	.9595	2.6073	4.2	-24.63
16		76.68	.002068	2.12	.6882	1.8605	-1.0	-14.24

coefficient, Cl, was derived from the wing lift force determined by subtracting the tail load, deduced from wind tunnel data, from the aircraft weight.[2] The horizontal tail angle of attack was determined by combining the aircraft angle of attack, the tail incidence angle, and the wing-induced downwash angle at the aerodynamic center of the tail, as generated by the vortex lattice computer program.

An analysis of the sources of the test results pertaining to the flow field about the horizontal tail, presented in Table 7, reveals some limitations to the accuracy of the data. Solies attributed a portion of the disagreement between the theoretical and experimental results to the required simplification of the simulation, which used a limited number of panels and neglected the effects of viscosity, wing and tail thicknesses, and the presence of the fuselage and vertical tail.[2] In addition, some uncertainty is present in the transient data, such as the aircraft angle of attack, the elevator deflection angle, and the tuft angles, due to the requirement for frequent control adjustments to maintain a relatively constant attitude with a longitudinally unstable aircraft.[2] The error between the theoretical and measured downwash angles varied in magnitude from 0.07 to 8.78 degrees, with no recognizable trend with respect to the test parameters. The average magnitude of the downwash error was 3.68 degrees. Yet, the results do indicate clear trends in the behavior of the flow field

Table 7. Aircraft Configuration and Downwash Angles from the 1985 Flight Tests

No.	Flaps (deg)	α (deg)	iT (deg)	εT (deg)	αT (deg)	δe (deg)	εerr (deg)
1	0	18.2	2.80	9.91	11.09	-4.0	-8.78
2		14.0	2.80	4.98	11.82	-3.2	-8.75
3		11.5	1.50	2.74	10.26	-4.2	-3.56
4		9.5	2.05	2.22	9.33	-4.0	-2.35
5	15	18.0	1.75	17.00	2.75	-0.5	1.62
6		12.0	1.75	11.45	2.30	-0.5	-0.38
7		12.5	2.05	10.54	4.01	-2.0	0.07
8		10.0	1.95	8.10	3.85	-1.0	-2.14
9		9.0	1.80	8.41	2.39	-2.0	0.08
10		4.5	2.05	5.26	1.29	-1.5	-1.72
11	30	12.0	2.98	13.57	1.41	0.7	-8.47
12		5.0	1.70	12.01	-5.31	0.0	-3.20
13		2.0	1.80	9.19	-5.39	0.0	-5.03
14		1.0	3.02	8.06	-4.04	0.7	-3.88
15	45	4.2	-0.90	27.93	-24.63	2.0	0.79
16		-1.0	-0.15	13.09	-14.24	1.2	-8.10

about the horizontal tail. The data were used in the current analysis since it allows for a determination of the downwash effect of the upper surface blowing wing on the horizontal tail surface, as will be shown in a later section.

2.3. Stall Characteristics of the NACA 0008 Airfoil

The horizontal tail of the Ball-Bartoe Jetwing is constructed about a NACA 0008 airfoil section. The basic dimensions, in percentage of chord length, of this section are provided in Table 8. This form is a thin symmetrical section, as depicted in Figure 3, with the flow velocity properties indicating a pressure peak close to the leading edge.[4] Thin, symmetrical airfoils typically reach maximum lift and stall at relatively small angles of attack, when compared to more conventional airfoils. For the NACA 0008 form, the angle of stall varies between 7 and 10 degrees, depending upon the Reynolds number. The lift and stall properties of the horizontal tail of the Jetwing are critical factors in the longitudinal stability of the aircraft.

Several studies have been made to determine the general stall characteristics of two-dimensional airfoils. Three predictable stall mannerisms have been defined from the results; trailing edge stall, leading edge stall, and thin airfoil stall.[5,6] These stall patterns are depicted in Figure 4. The trailing edge stall is usually associated with thicker airfoil sections, greater than 15% chord, and

Table 8. NACA 0008 Basic Thickness Form

x (% chord)	y (% chord)
0.0*	0.000
1.25	1.263
2.5	1.743
5.0	2.369
7.5	2.800
10.0	3.121
15.0	3.564
20.0	3.825
25.0	3.961
30.0	4.001
40.0	3.869
50.0	3.529
60.0	3.043
70.0	2.443
80.0	1.749
90.0	0.965
95.0	0.537
100.0	0.084

* Leading edge radius equals 0.70% chord.

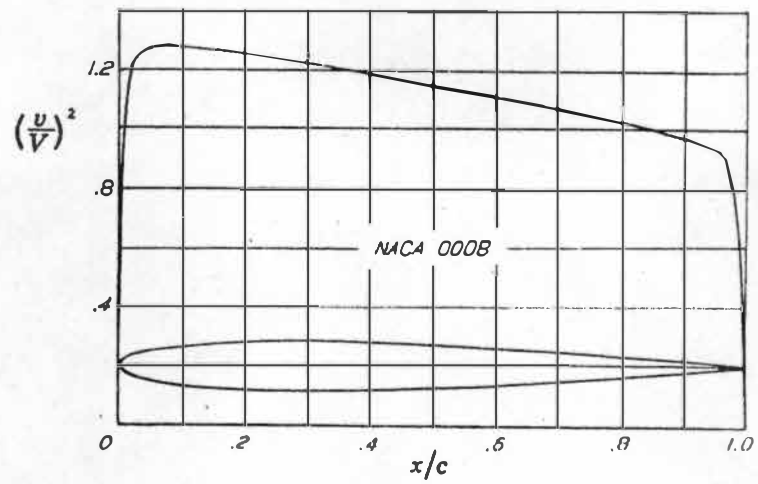


Figure 3. NACA 0008 Airfoil Section

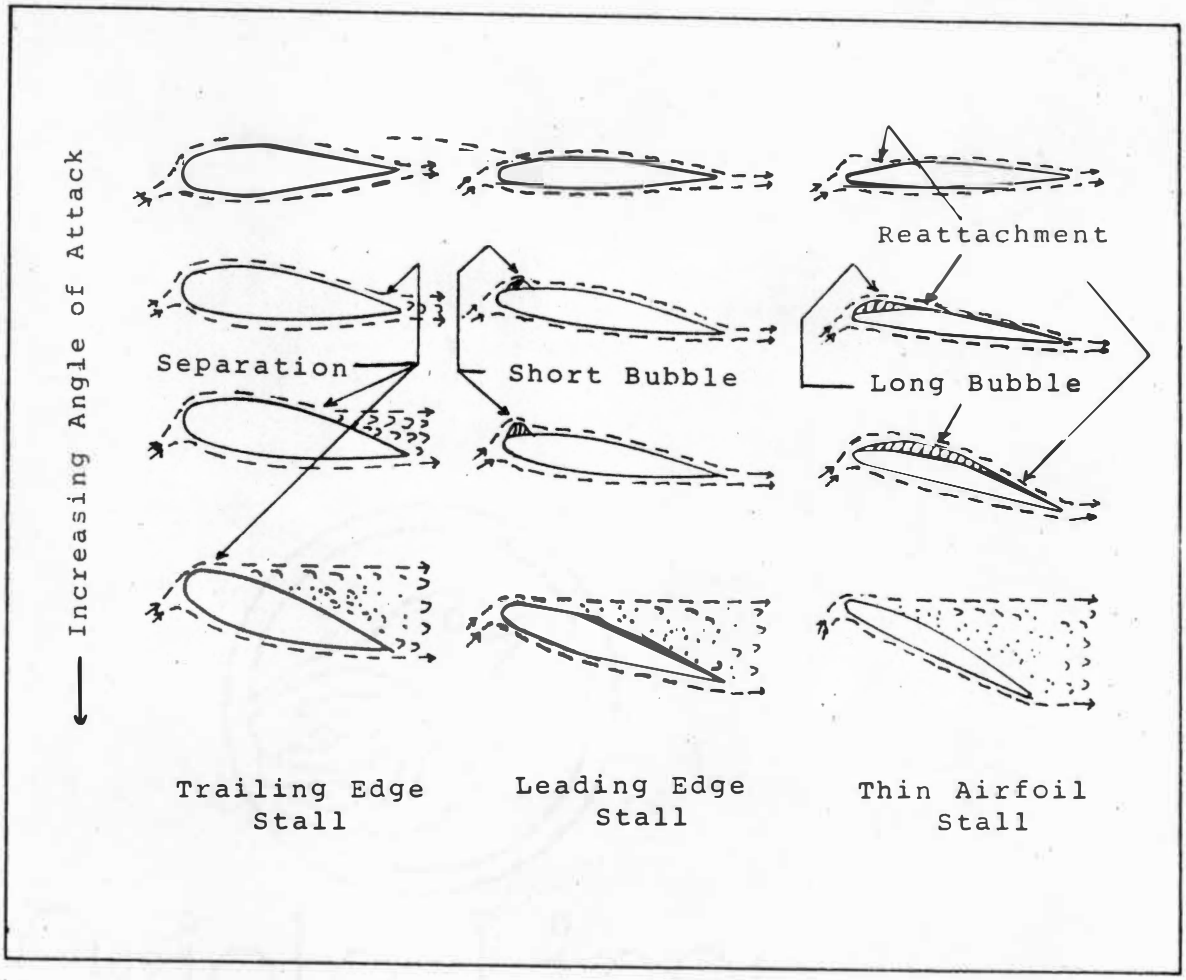


Figure 4. Three Types of Stall Behavior

is not of concern in this situation. On the other hand, both the leading edge stall and the thin airfoil stall are involved. A relationship has been defined between the stall properties, the airfoil shape, and the Reynolds number of the flow field.[5] As can be found in Figure 5, the NACA 0008 airfoil, in the flow field conditions determined by the UTSI Flight Operations tests, should experience thin airfoil stall behavior at low airspeeds and leading edge stall behavior at higher airspeeds with a transition somewhere in between.

The leading edge stall of an airfoil is identified as the sudden separation of the flow over the leading edge of the airfoil without reattachment further back along the surface. This type of stall appears very quickly at the critical angle of attack with only small disturbances prior to the stall due to the presence of a laminar separation bubble near the leading edge. The sudden rupture of this bubble, with the failure of the flow to reattach, creates the sharp peak in the lift curve commonly seen for thinner airfoil sections.[5]

A thin airfoil stall follows much the same pattern as the leading edge stall, but the flow field reattaches to the surface behind a longer separation bubble. The location of this reattachment point moves aft as the angle of attack increases until it passes beyond the trailing edge of the airfoil, and a complete stall develops. Thin, round-nosed

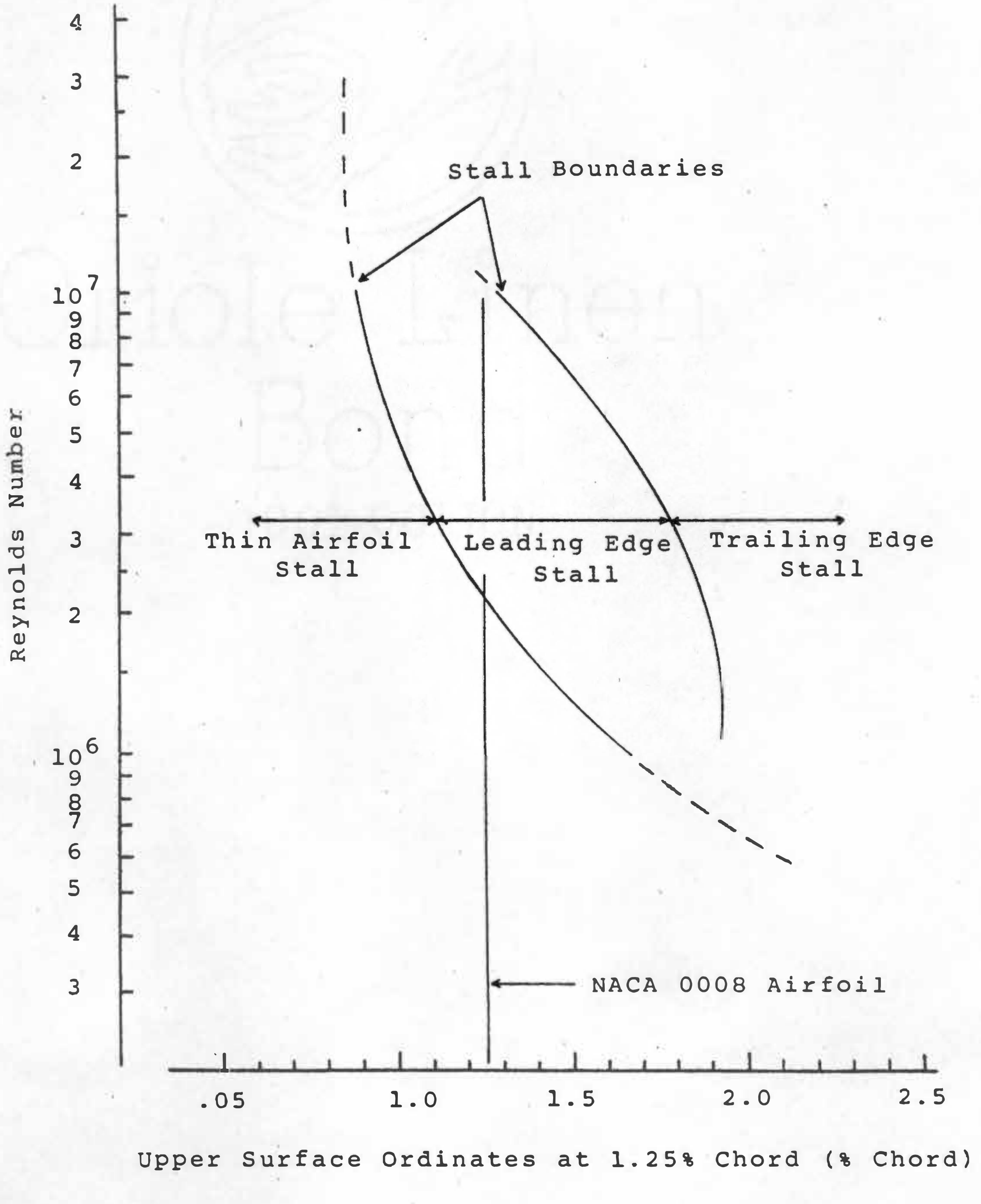


Figure 5. Gault Diagram, The Effect of Reynolds Number on the Stalling Characteristics of Clean Airfoil Sections as a Funtion of Airfoil Geometry

airfoils, such as the NACA 0008 section, have been observed to have lift curves which include a small discontinuity, due to the presence of the separation bubble, prior to a more rounded peak at the point of maximum lift.[5]

The location of this discontinuity on the lift curve varies with the Reynolds number, increasing in angle of attack as the Reynolds number is increased. For a large enough Reynolds number, the discontinuity is delayed until the airfoil experiences a leading edge stall. The stall behavior of the NACA 0008 airfoil has been experimentally determined to change at a Reynolds number of approximately 3 million.[6] The lift and drag curves for the NACA 0008 and the change in lift with varying Reynolds numbers are presented in Figures 6 and 7. This data also indicates that the shift in stall behavior is not necessarily a repeatable phenomenon, and that the lift discontinuity may occur at slightly varied angles of attack.

2.4. Elevator Deflection and Horn Balance Effects

A study of the available literature pertaining to the application of thin airfoils as flight control surfaces, as in the case of the Ball-Bartoe Jetwing, revealed the lack of data concerning the NACA 0008 airfoil section. Fortunately, the NACA 0009 section, from the same airfoil family, has been subjected to a few of these types of tests. These two airfoil shapes are very similar, differing only by one

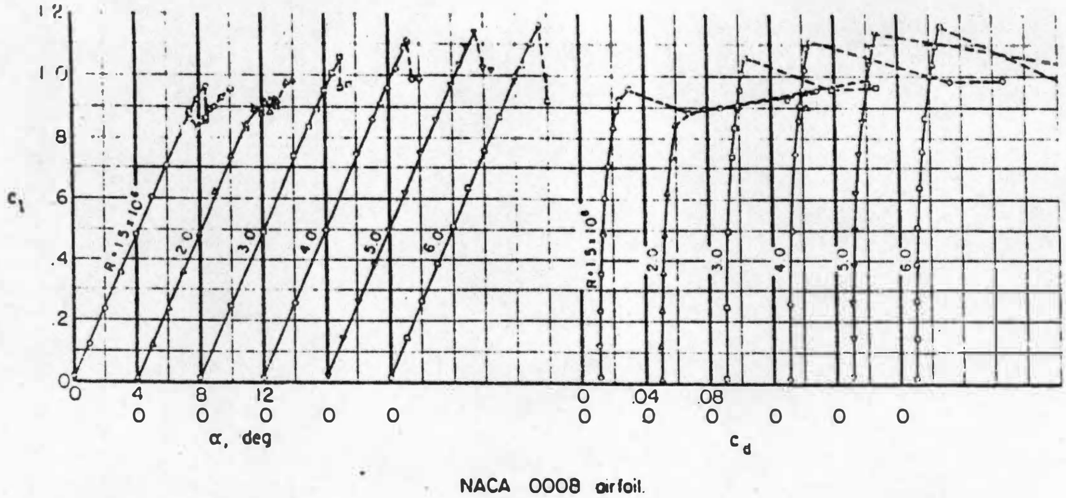


Figure 6. Aerodynamic Section Characteristics of a NACA 0008 Airfoil for Various Reynolds Numbers

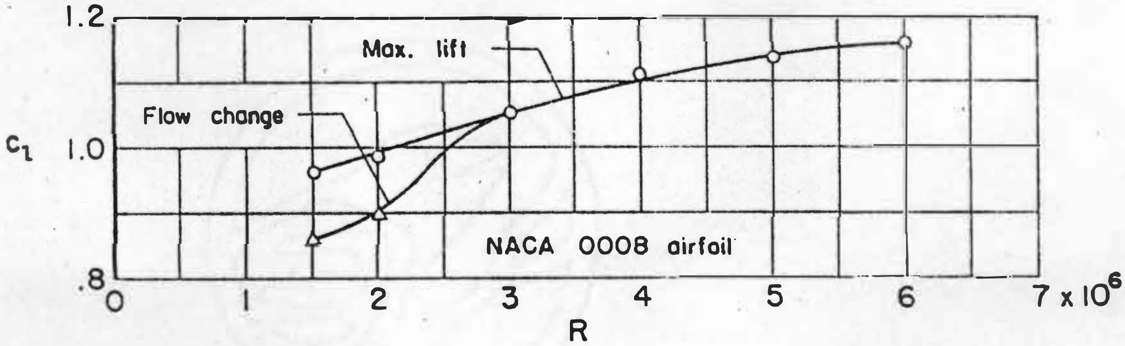
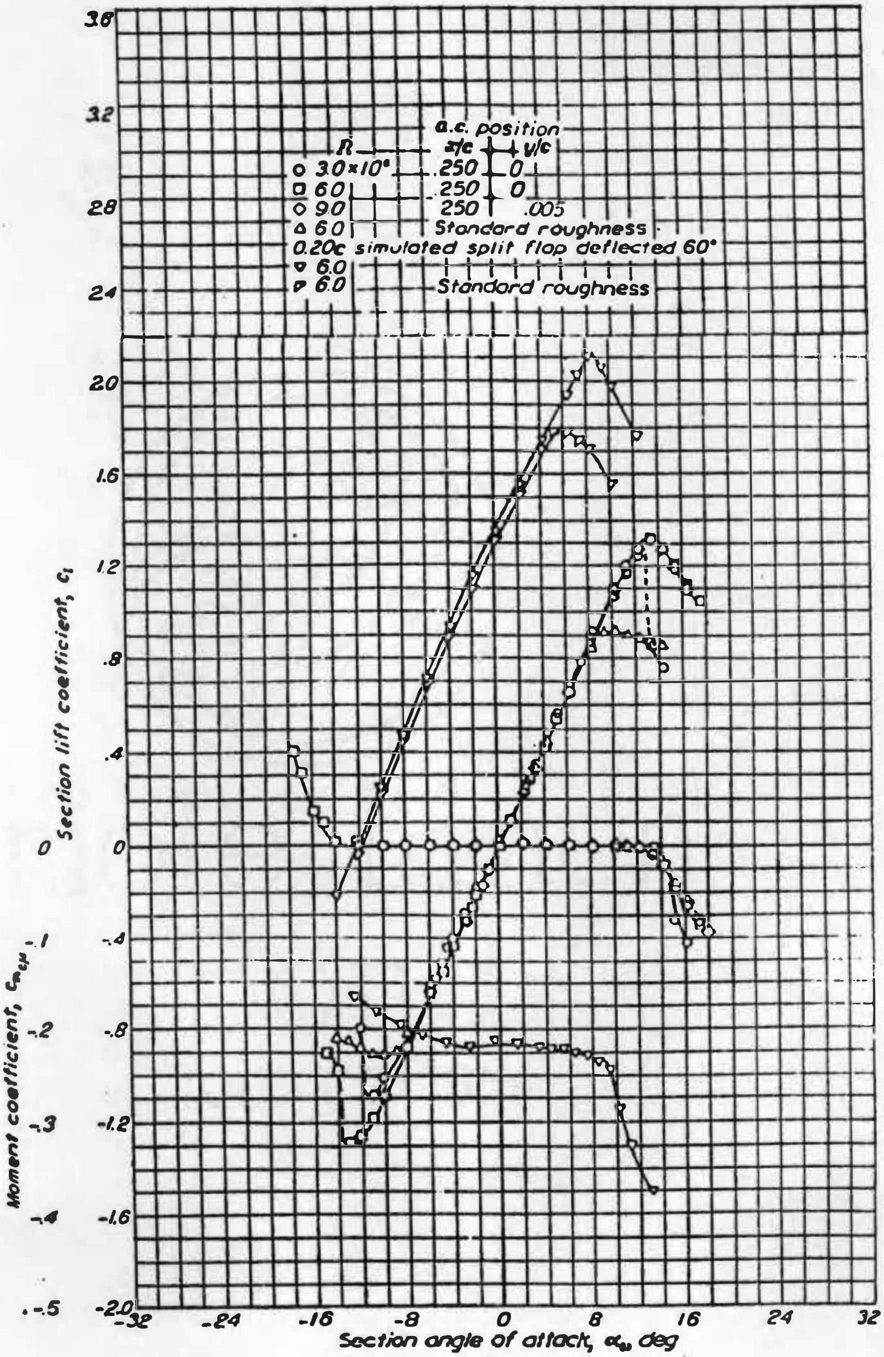


Figure 7. Change in Lift Coefficient for a NACA 0008 Airfoil as a Function of Reynolds Number

percent of the chordlength at the point of maximum thickness, therefore the lift characteristics could be expected to be similar. Test results indicate that the NACA 0009 section stalls at a slightly higher angle of attack, as determined by a comparison of the lift curves for the two airfoil sections, Figures 6 and 8. In light of these similarities, the test results from a NACA 0009 airfoil should be be generally applicable to a flight surface with a NACA 0008 section. Any error due to the difference in airfoil thickness is quickly consumed by errors arising from real surface roughness, surface deformations, and manufacturing errors.

The elevator on the horizontal tail of the Jetwing is a plain design with a length of approximately 40 percent of the airfoil chord. The gap between the elevator overhang and the tail surface is not sealed and measures roughly one half of a percent of the chord. The deflection of an elevator of this size has a significant effect on the airflow over the surface. A NACA 0009 airfoil has been tested with a 50 percent chord plain flap and a similar gap size, across a series of deflection angles and with the gap both sealed and unsealed. The results of these tests, as published in NACA TN 1517, are presented in Figures 9 and 10. Sealing the gap produced a slight increase in the lift effectiveness and the lift curve slope of the airfoil section.[7] This small effect is not apparent at the trim condition and was



NACA 0009 Wing Section

Figure 8. Aerdynamic Section Characteristics of a NACA 0009 Airfoil for Various Reynolds Numbers

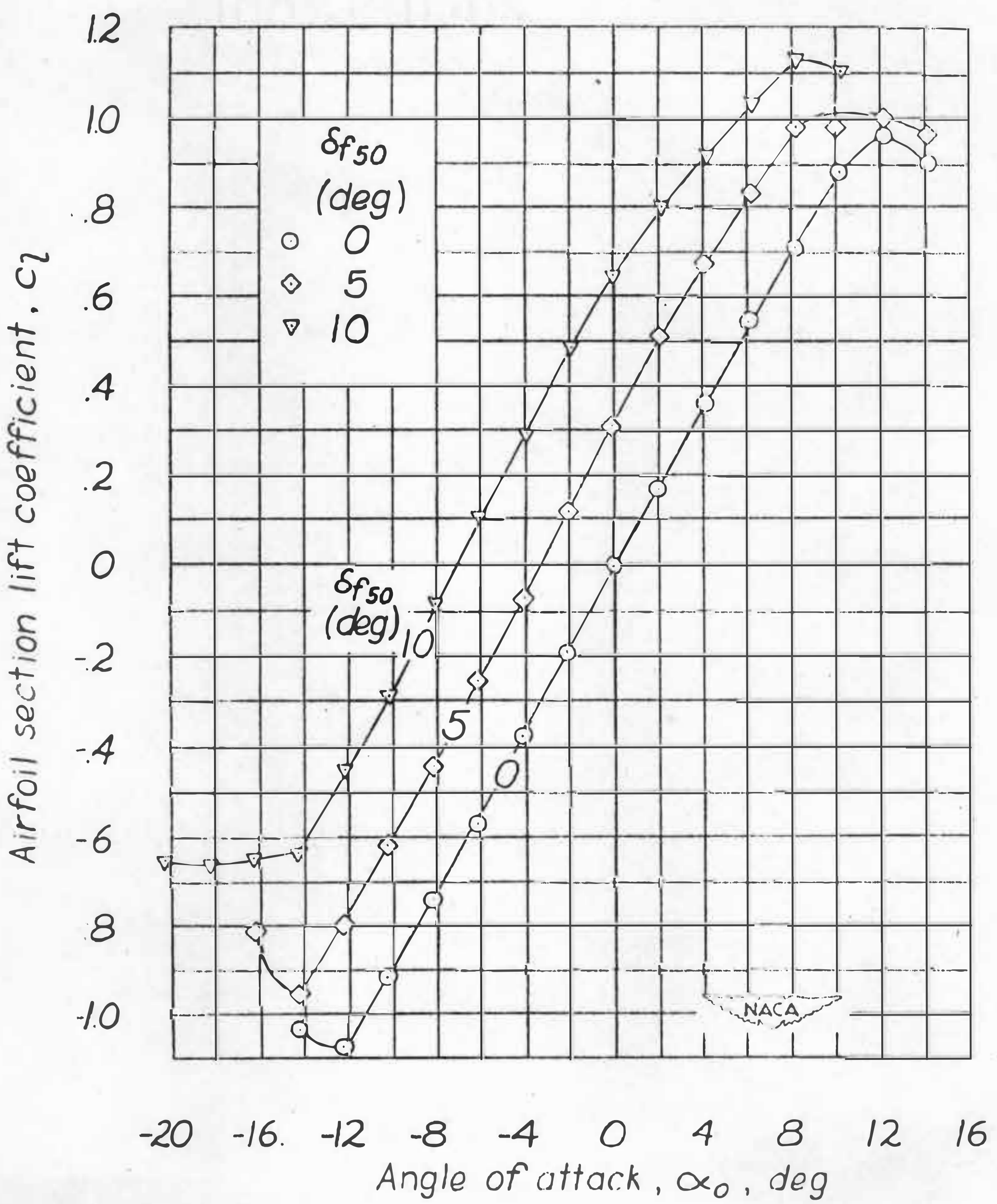


Figure 9. Aerodynamic Section Characteristics of a NACA 0009 Airfoil with a 0.50c Plain Flap and a 0.005c Gap at a Reynolds Number of 2,580,000

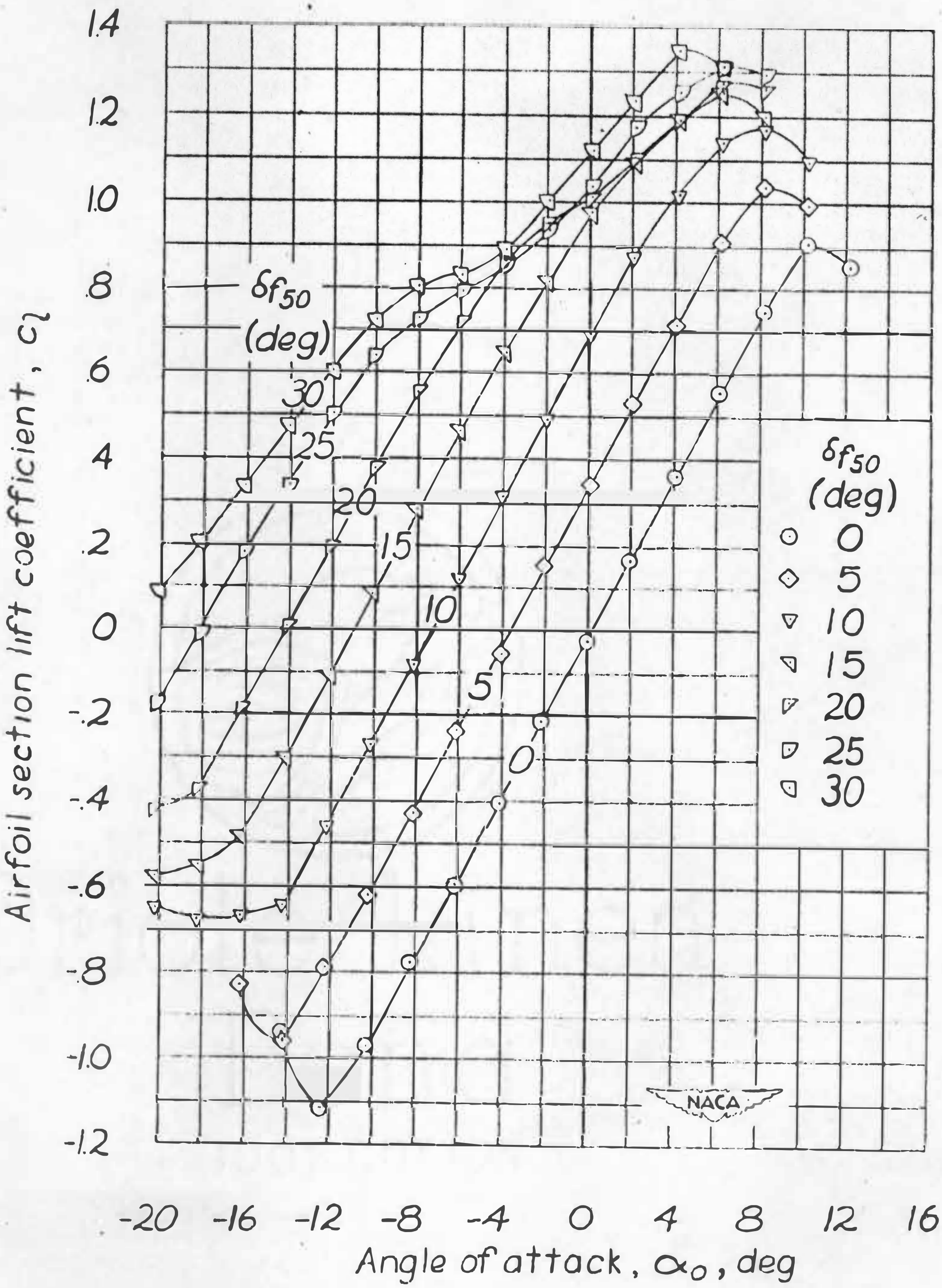


Figure 10. Aerodynamic Section Characteristics of a NACA 0009 Airfoil with a 0.50c Plain Flap and a Sealed Gap at a Reynolds Number of 2,580,000

judged to be insignificant in terms of the cost and difficulty of retrofitting a sealed gap to the tail. As the deflection angle of the flap was increased, a fairly linear increase in the lift curves was evident, until the deflection angle reached 15 degrees. Beyond this point, the separation of the flow from the surface, due to the abrupt discontinuity at the hinge point, created highly turbulent flow which reduced the available lift. The horizontal tail of the Jetwing could reasonably be expected to follow the same type of behavior.

The horn balance on the elevator surface of the horizontal tail of the Jetwing is shielded by the leading edge of the tail. The proper application of horn balances to aircraft control surfaces should increase the stick free stability of the aircraft, a benefit that is offset by an increase in the required control forces.[8] It was evident that the designers of the Jetwing intended to take advantage of this additional stability factor by the inclusion of such a balance in the tail design. Unfortunately, the shielded horn used on the Jetwing is less effective than an exposed design, which would extend to the leading edge of the surface. Any heaviness in the flight controls must be assumed to have been negligible, owing to the instability of the aircraft, since none of the test pilots commented on this point and the data reveals no indication of such a condition. Previous testing, published in NACA TN 2495, had determined that a horn balance of the type and design used on the Jetwing, while balancing the elevator forces and moments, should have very little effect on the lift effectiveness of the horizontal tail as a whole.

2.5. Summation of the Problem

A review of the available information concerning the flow field about the horizontal tail of the Ball-Bartoe Jetwing was required before a solution could be proposed. This information had been drawn from the UTSI Flight Operations evaluations of the flight vehicle and combined with the results of experimental tests involving plain airfoils. The flow situations at the horizontal tail for the various flap settings at a representative airspeed have been compiled from the flight test data and presented in Figure 11. From an examination of these diagrams, it was apparent that an increase in flap deflection had a direct influence on the flow field about the horizontal tail. As the flap was deflected further, the tail experienced a gradually decreasing positive angle of attack until the flow crossed the plane of the tail and created an increasingly negative angle of attack. For flap settings from 0 to 15 degrees, the positive angle of attack of the horizontal tail was converted into a stabilizing negative lifting force by an opposing elevator deflection. During larger flap deflections, no elevator deflection was required to produce the negative

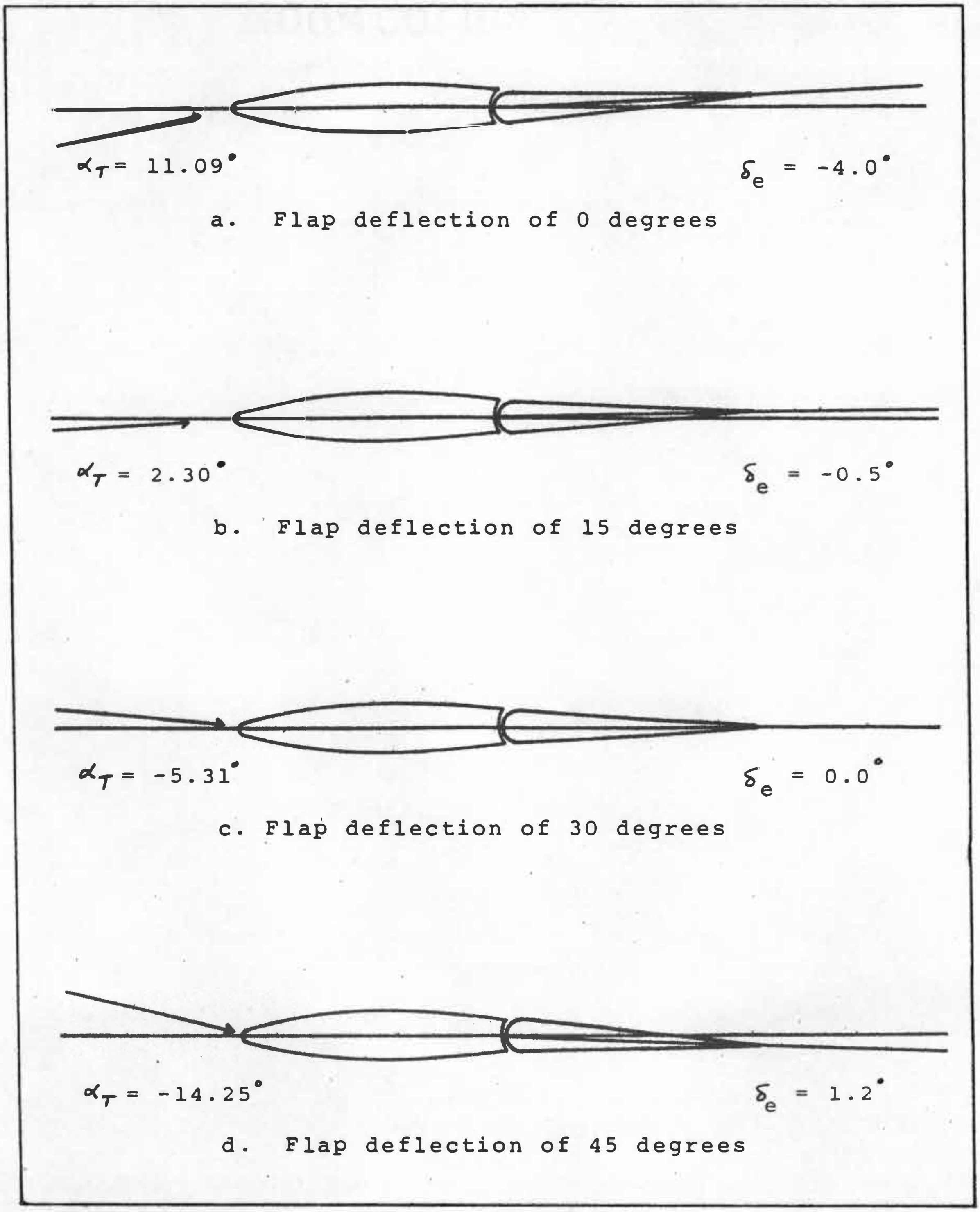


Figure 11. Horizontal Tail Conditions for Various Flap Settings at an Airspeed of 70 KIAS

lifting force, since the tail surface was at an appropriate angle of attack. Indeed, the angle of attack became so great as to cause the tail surface to stall in some situations. To increase the longitudinal stability of the Jetwing, the lift characteristics of the horizontal tail must be improved to better handle the wide variations in the flow angle, which are beyond the capability of the current NACA 0008 airfoil, and to prevent the occurrence of a tail stall.

Any changes to the Jetwing for the purpose of improving the tail effectiveness must be carefully evaluated within the framework of several constraints. First, the narrow range available for the aircraft center of gravity restricts the addition of any weight at an extreme aft position, such as the horizontal tail. Any amount of mass added in the tail region must be balanced by an even greater amount of ballast in the nose, due to the shorter moment arm to the forward location. Second, the improvements must require no input from the pilot or must be simple to operate, due to the inherent difficulty already present in piloting an unstable aircraft. Lastly, the improvements should be cost effective, since any modifications would be financed by the University of Tennessee. Thus, any proposed solution to improve the tail effectiveness, as a means of correcting for the longitudinal instabilities of the Jetwing, must be evaluated with respect to these constraints of weight, complexity, and cost.

3. SEARCH FOR SOLUTIONS

3.1. Lift Augmentation Systems

A major hazard in the longitudinal stability of the Ball-Bartoe Jetwing has been the recurring horizontal tail stall in low airspeed, high power configurations. In order to determine a method of delaying or preventing the stall, several lift augmentation mechanisms for the horizontal tail were examined. Each of these systems was evaluated with respect to the criteria for weight, complexity, and cost. The available literature contained many concepts for improving the lift and stall characteristics of a plain airfoil section, but the majority of this information was directed to improving the effectiveness of the aircraft wing. The application of these mechanisms to other flight surfaces, such as the horizontal tail, has yet to become an issue of any great importance.

The most basic improvement to the effectiveness of the horizontal tail could be achieved by the replacement of the present tail surface with a newly designed tail. Such a redesign process should take advantage of a thicker, perhaps cambered, airfoil section. The introduction of a larger planform area would increase the tail volume of the Jetwing, as recommended by the UTSI Flight Operations.[1] Changing the incidence angle of the tail plane could improve the angle of attack situation due to the downwash from the blown flap. Indeed, an all-moving stabilator would greatly improve control effectiveness and stability by allowing for a larger effective control surface and possessing the capability of being trimmed for a wide range of flow angles. A redesign effort should also examine the possibility of positioning the horizontal tail at the top of the vertical tail to avoid as much of the downwash as possible, although this configuration would require the strengthening of the vertical tail structure. Any substantial modification to the tail design would necessitate complex structural considerations of the tail and fuselage, due to the added, and possibly repositioned, weight of the extra surface area. The design and fabrication of an entirely new tail would be a relatively intricate and expensive project, though the end result should be successful if properly executed.

Energizing the boundary layer flow about the horizontal tail would also increase the tail effectiveness by delaying or reducing flow separation. The application of a traditional boundary layer bleed control, which would absorb the turbulent air layer through the perforated surface of the tail, would add another level of complexity to the aircraft. The requirements for routing suction lines from the engine or other source, the additional weight of the suction bleed plenum within the tail, and the difficulty of maintaining the system in an operable condition severely limited the feasibility of such a system in this application.

A more encouraging concept, especially in terms of the large deflecting control surface involved, was the addition of a rotating cylinder along the hinge line of the elevator, as shown in Figure 12.[9] The cylinder would help to energize the flow over the elevator and reduce the flow separation which occurred at deflection angles greater than about 15 degrees. At smaller deflection angles, the flow had not yet separated from the surface and the advantages of the cylinder are lessened. This mechanism was developed for a wing and flap, where the cylinder would rotate in a constant direction. When applied to an elevator, the cylinder must be capable of rotating in both directions to provide a consistent boundary layer control for both positive and negative deflections of the elevator. The additional drawbacks to such a system are the requirements for a drive source for the cylinder, either electrical or pneumatic, the additional weight of the cylinder in such an aft location, the resulting complexity of the hinge, and the reduced benefits at lower deflection angles. The basic restrictions of providing a secondary power source defeat the prospects of applying such powered lift augmentation systems to the tail surface.

Mechanical high lift systems, which derive supplementary lift directly from the energy of the flow stream rather than an additional power source, are simpler and usually lighter than powered systems. The conventional

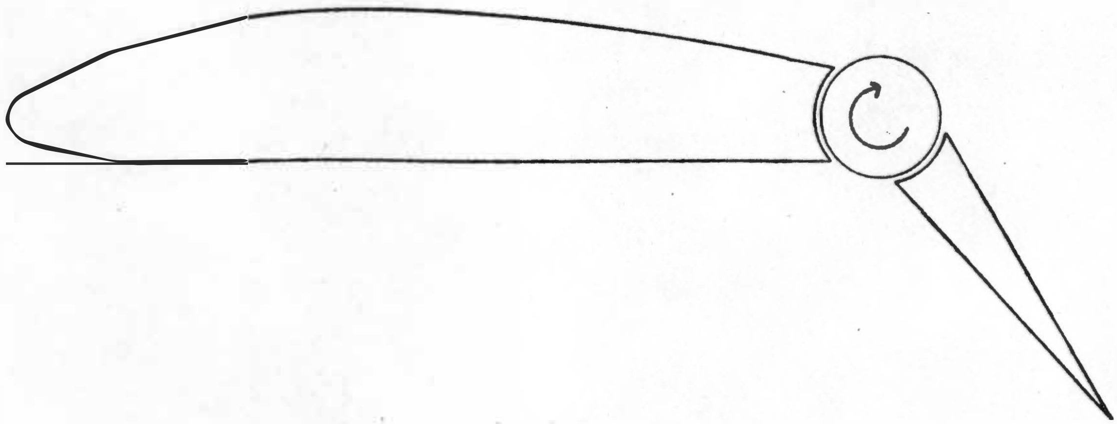


Figure 12. Rotating Cylinder Located Along the Hinge Line of the Flap

systems have often been used in the wing designs of modern commercial and military aircraft and, to a lesser degree, in general aviation aircraft.[10,11] Increasing the radius of the leading edge of an airfoil section prevents early flow separation at small angles of attack. Drooping the leading edge about a camber line forward of the 15 percent chord location of the airfoil, Figure 13, improves the lift characteristics further but also begins to increase drag. The drag rise can be countered by the use of a movable leading edge flap, as presented in Figure 14. This design minimizes drag at cruise conditions but can be deployed to provide the additional camber required for additional lift at lower airspeeds.[10]

The lifting capability of an airfoil can also be increased by expanding the area of the lifting surface. Extending the chord length of the surface, with the benefit of the additional camber included, is the purpose of the Kruger leading edge folding flap, Figure 15. The Handley Page leading edge slat is capable of all of the above with the additional advantage of possessing a slot which entrains and energizes the flow over the upper surface of the airfoil, as shown in Figure 16.[11] All of these systems are still relatively heavy, and the additional controls required to deploy the surfaces severely reduced the advantages of these systems for the Jetwing, due to the increase in pilot workload.

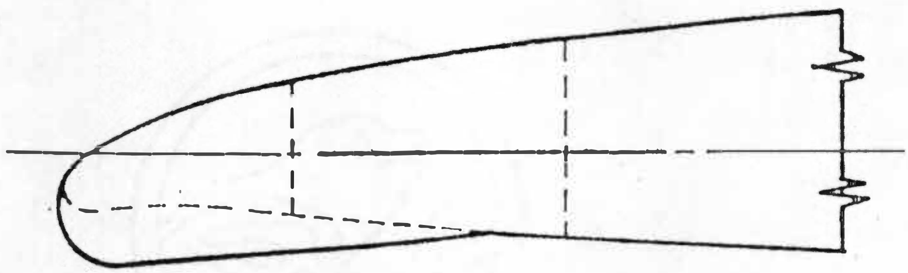


Figure 13. Increased Leading edge Radius and Drooped Camber Modifications to an Airfoil

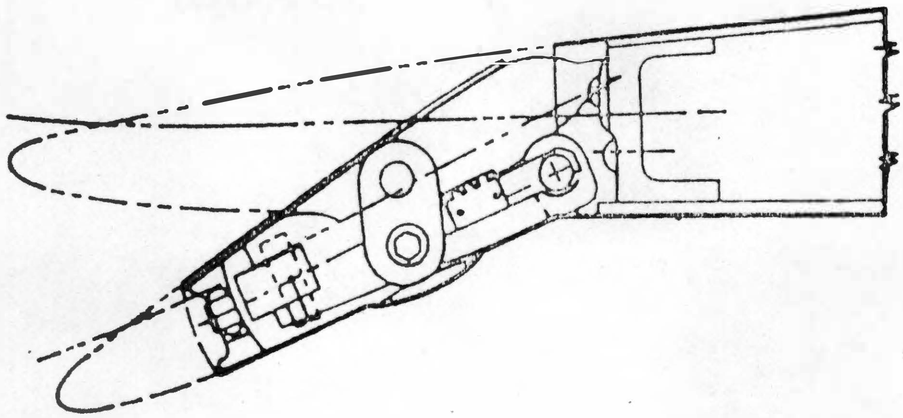


Figure 14. Leading Edge Flap Mechanism in the Deployed Position

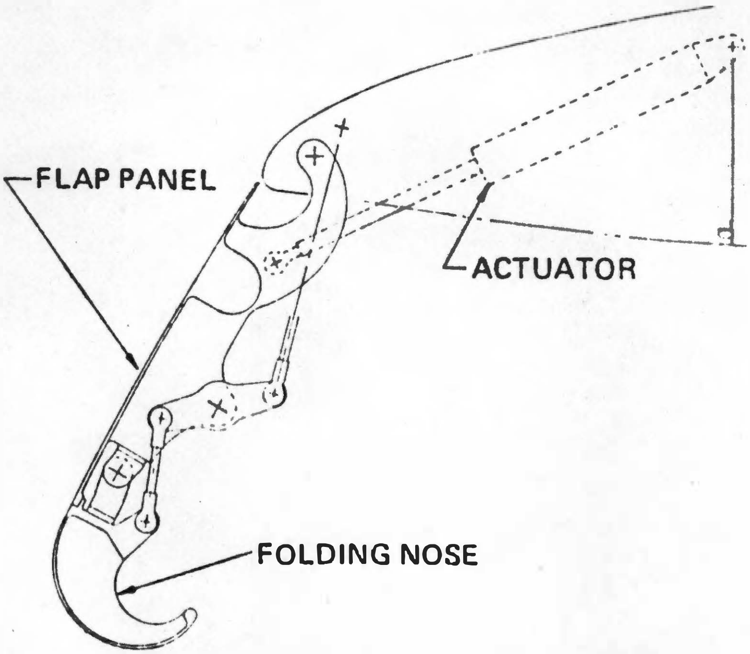


Figure 15. Kruger Leading Edge Folding Flap in the Deployed Position

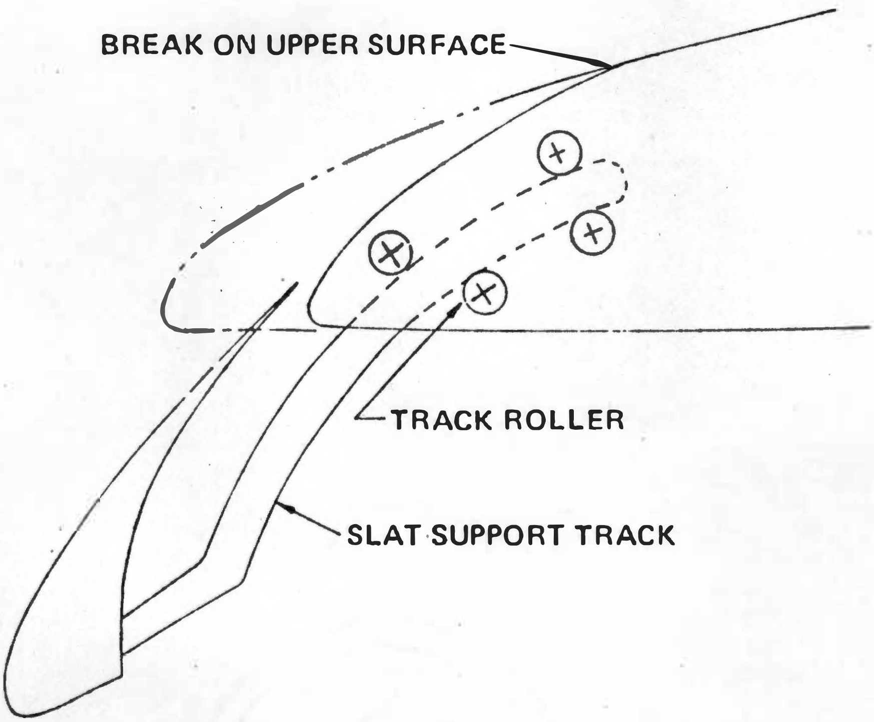


Figure 16. Handley Page Leading Edge Slat in the Deployed Position

Simpler fixed lift augmentation systems, which remain deployed at all times, remove the complexity of an additional controllable surface but have the disadvantage of increased drag. A fixed slat is a variation of the deployable slat concept, as depicted in Figure 17. The additional drag created by the fixed surface is minimized by limiting the effective camber of the slat, but the flow is still entrained over the surface of the airfoil to delay separation at increased angles of attack.[12] Vortex generators and flow fences also fall into the category of simple, fixed mechanisms, but neither of these approaches provides enough influence over the flow field to be capable of controlling the extremely turbulent flow experienced by the horizontal tail. Other fixed mechanism concepts, such as the augmentor wing and the internally slotted airfoil, which have proved successful when applied to wing surfaces, would be very difficult to implement in the current situation involving horizontal tail surfaces.[9,13] From this varied field of options, a system or combination of systems would have to be selected as the most appropriate candidate for application to the Jetwing.

3.2. Selection of the Fixed Slat

To prevent the horizontal tail stall experienced by the Ball-Bartoe Jetwing at low airspeeds, the tail must be modified to raise the angle of stall or reduce the angle of

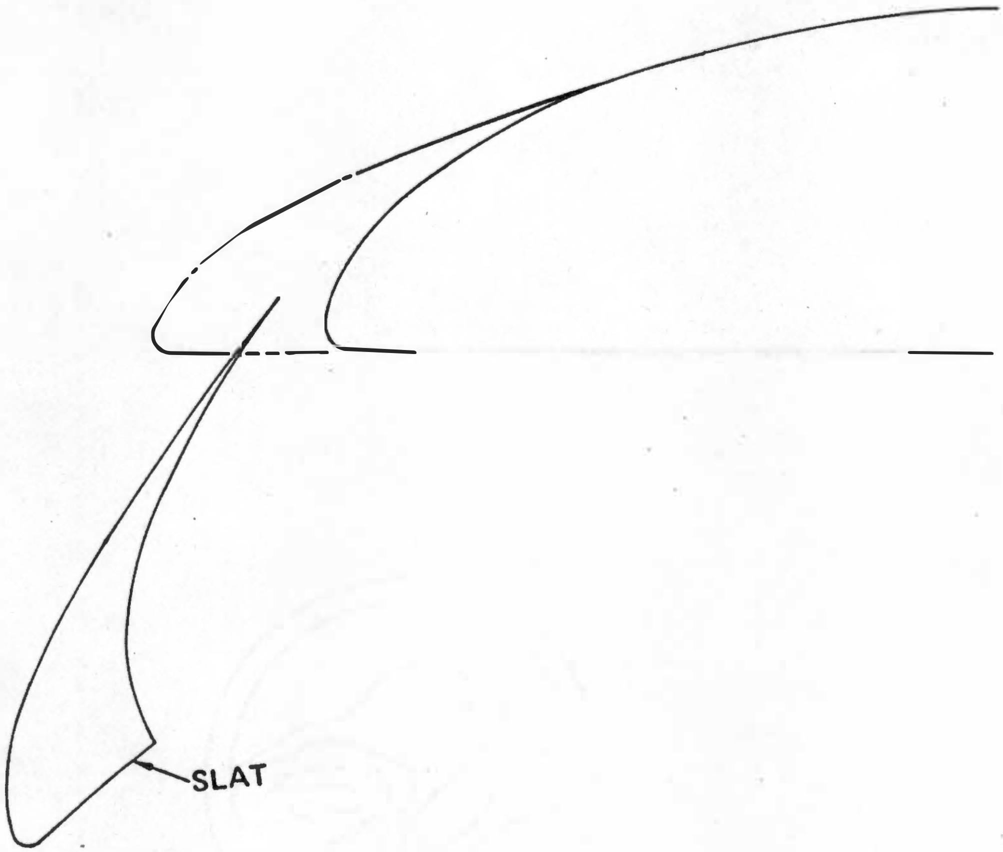


Figure 17. Fixed Slat Cut From the Leading Edge of an Airfoil and Projected to Increase Camber

the incident flow. The tail must also be modified to provide for some inherent stall resistance to protect against such situations. Of the variety of lift augmentation systems reviewed, the fixed slat provides the most viable solution to the problem.

A fixed slat, as described earlier, would improve the lift characteristics of the horizontal tail in several ways. The proposed design would increase the leading edge radius of the airfoil section and would increase the total planform area of the tail. More importantly, the flow through the slot would energize the boundary layer over the tail surface, which should improve both the maximum lift coefficient and the angle of stall. The increased lift would have the same effect as increasing the planform area, while improving the stall behavior of the tail and minimizing the added weight. The fixed slat has been proven to be a reliable source of additional lift, and the lack of any auxiliary control systems would provide a safer system due to the constant capacity for stall resistance. The proposed design of the slat, based upon recent advances in the field, would be a very light weight addition and should produce a minimal amount of added drag to the aircraft. Due to the simplicity of the design, which would facilitate the fabrication and installation of the slat, the addition of this mechanism would be a relatively inexpensive project. An analysis of the experimentally determined benefits of installing a fixed slat on an airfoil provided some assurance that such a modification to the Jetwing would produce the desired results.

4. PROPOSED SOLUTION

4.1. Justification for Selection

The most appropriate solution for the longitudinal stability problems of the Ball-Bartoe Jetwing, due to the aforementioned constraints of weight, complexity, and cost, would be the application of a fixed slat to the leading edge of the horizontal tail. The significant advantages of the fixed slat over any mechanical lift augmentation system include "greater simplicity and dependability, less weight, less maintenance, and somewhat lower cost."[12] The major advantages of the slat over any of the other fixed systems are due to the extremely light weight of the proposed thin slat and the position it occupies on the leading edge of the tail, minimizing the need for additional ballast. The primary disadvantage of a fixed slat is the increase in drag created at low angles of attack, although the drag rise should be limited by a proper slat design.

A large amount of research was performed at the Langley Memorial Aeronautical Laboratory in the early 1930s to determine the effects of fixed slats mounted on Clark Y airfoils. The original slat airfoil shape was created by separating a piece of the leading edge from the airfoil to produce a slot which would possess a natural boundary layer control, see Figure 17. In subsequent testing, the slat airfoil was contoured to reduce the drag penalty, and the position of the slat was varied to investigate the performance benefits. From these tests, the researchers learned that the position of the slat was of greater importance than either the size or the shape of the slat airfoil.[14] The drag rise was also determined to be insignificant in relation to the total drag on the aircraft. The optimum positions and shapes for a slat mounted on a Clark Y airfoil were determined for the cases of the maximum lift coefficient and the maximum lift angle.[14] Unfortunately, these slat designs were not coincident, although the maximum lift angle was of lesser importance. The addition of a fixed slat was recommended for aircraft with low airspeed requirements, since the slat would enable the aircraft to reach such airspeeds with a smaller lifting surface.[12] These characteristics apply directly to the Jetwing situation, where safe minimum airspeeds are desired without increasing the size of the horizontal tail.

The design of the thin, fixed slat proposed for the Jetwing is based, in part, upon the test results presented by Karl H. Bergey of the University of Oklahoma.[15] The thin, fixed slat was first created and tested on the wing leading edges of a Rockwell/Ayres S-2R agricultural aircraft. The slat design was based upon goals similar to those for the Jetwing tail. The researchers wished to obtain a higher maximum lift coefficient with minimal drag penalties, using a system that would be inexpensive to produce and simple to fit to existing structures. Starting from the concept for the conventional contoured slat of the dimensions suited to the wing airfoil section, Figure 18, the investigators modeled a thin slat, Figure 19, that would approximate the flow behavior of the conventionally shaped slat. The thin slat performed nearly as well as the contoured slat in computational flow simulations, and the ability to fabricate the thin slat from rolled aluminum sheeting greatly simplified production and lowered the cost of the modification.

4.2. Design Details of the Proposed Slat

The proposed slat for the horizontal tail of the Ball-Bartoe Jetwing would be fabricated from rolled aluminum sheeting, similar to the slat designed by Bergey. The primary dimensions of slat geometry are the cut-off and maximum thickness of the slat, and the gap, width, and depth of the slot between the slat and the airfoil, as depicted in Figure 20.[14] An analysis of the test results of airfoils fitted with slats mounted in a variety of positions produced an indication of the optimum values for these critical dimensions, Table 9. Based upon these optimum dimensions for a traditional contoured slat, the dimensions developed for a thin slat, and standardized dimensions for ease of fabrication, an ideal slat was designed for the mean airfoil chord.

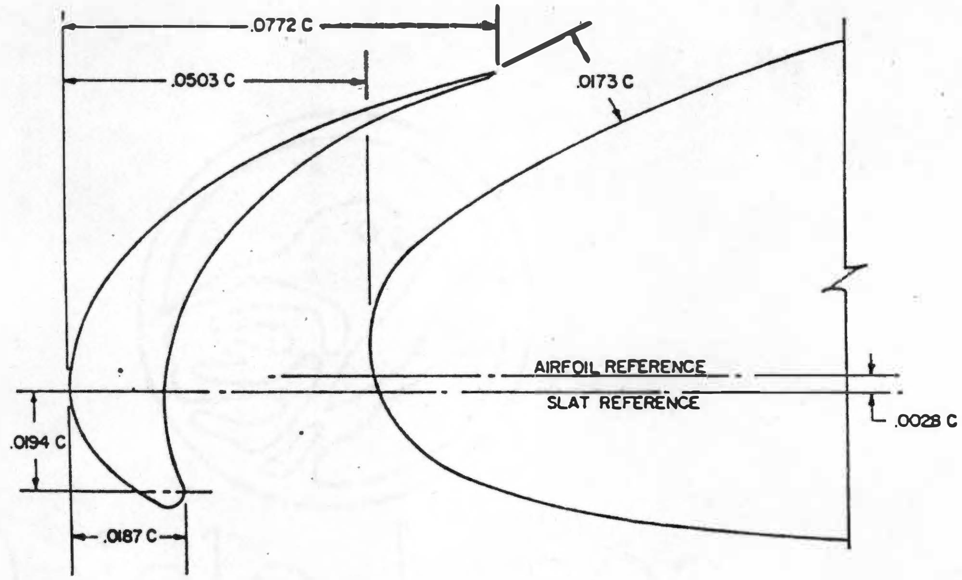


Figure 18. Conventional Fixed Slat Design for the Rockwell/ Ayres S-2R Wing Section

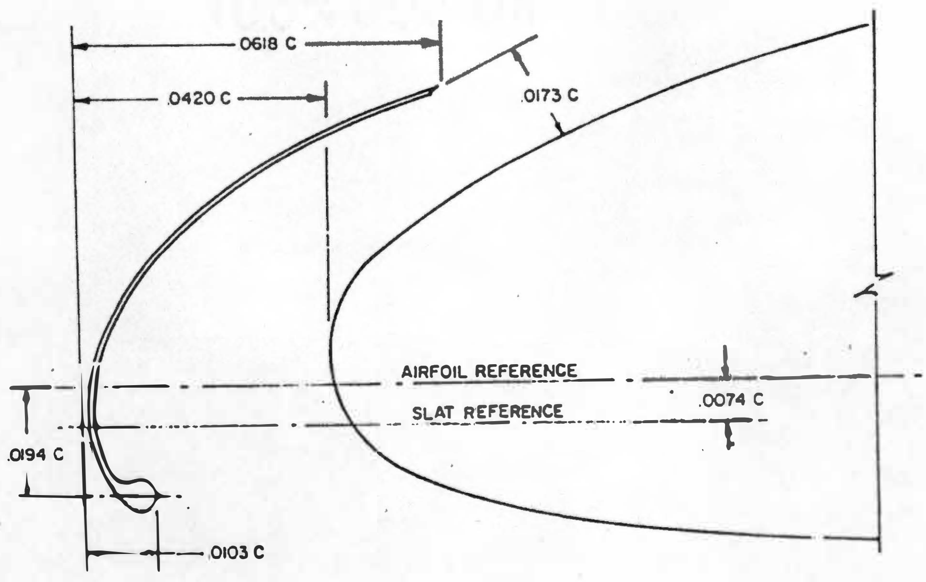


Figure 19. Thin Fixed Slat Design for the Rockwell/Ayres S-2R Wing Section

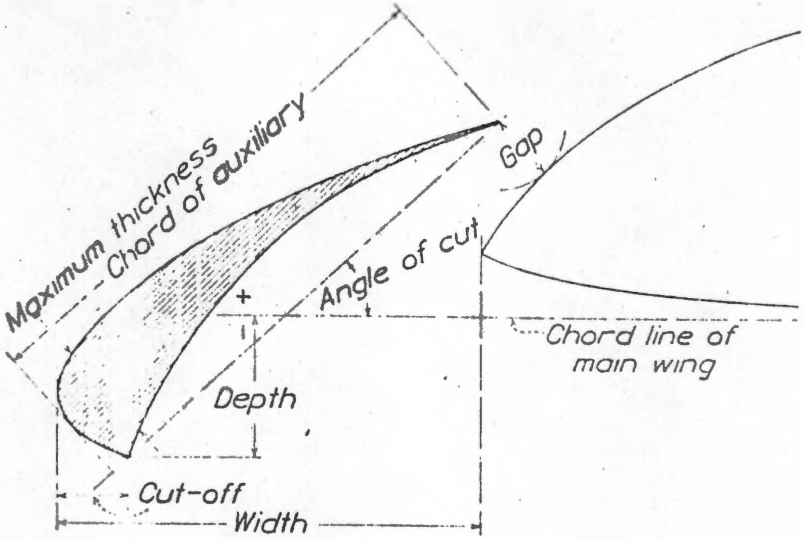


Figure 20. Geometric Factors in Slat Design

Table 9. Optimum Dimensions of the Geometric Factors in Slat Design

Geometric Factor	Minimum, % chord	Maximum, % chord	Average of best results, % chord
Auxiliary Airfoil Chord	8.34	28.80	14.70
Cut-off	*	2.00	1.85
Maximum Thickness	*	2.80	2.50
Slot Gap	2.08	3.75	2.50
Slot Width	6.68	17.50	13.00
Slot Depth	+3.31**	-4.00	-3.00

* Thin plate
** Indicates above (+) or below (-) airfoil chord line

The mean chord was determined by limiting the spanwise length of the slat to a distance extending from the tail root to the inboard edge of the horn balance. The span of the slat was terminated at the edge of the balance since any deflection of the elevator and horn disrupts the shape of the airfoil section. The slat designed for the mean chord-length was then adjusted for the range of dimensions at the minimum and maximum chordlengths. Creating a single slat profile which would be suitable at each of the minimum, mean, and maximum chordlengths was vital to allow for a slat with a constant cross-section. The fabrication of such a slat would be much simpler than that for a slat with a spanwise variation in shape.

The resulting dimensions of the proposed slat design at the minimum, mean, and maximum chord positions have been listed in Table 10, along with the optimum ranges for these values. The relative sizes and positions of the proposed slat at each of these chord positions are depicted in Figures 21, 22, and 23. The planform view of the modified horizontal tail is presented in Figure 24. The slat is located on the lower surface of the horizontal tail since its purpose is to protect against the stall caused by extreme downwash angles and to increase the negative lift of the tail. Conventional slats have been installed on the upper surface of the wing to improve the normal lifting capability of the wing.

Table 10. Dimensions of Geometric Factors for the Proposed Thin Slat

Geometric Factor	Physical Size (in)	Minimum Chord Position (%chord)	Mean Chord Position (%chord)	Maximum Chord Position (%chord)	Optimum Range (%chord)
Slat Chord	5.25	17.80	14.29	11.93	11.5-14.7
Cut-off	0.50	1.69	1.36	1.14	1.03-1.85
Slot Gap	0.75	2.54	2.04	1.70	1.73-3.00
Slot Width	3.50	11.86	9.52	7.95	4.20-13.0
Slot Depth	0.625	-2.12	-1.70	-1.42	-1.5-(-3.0)

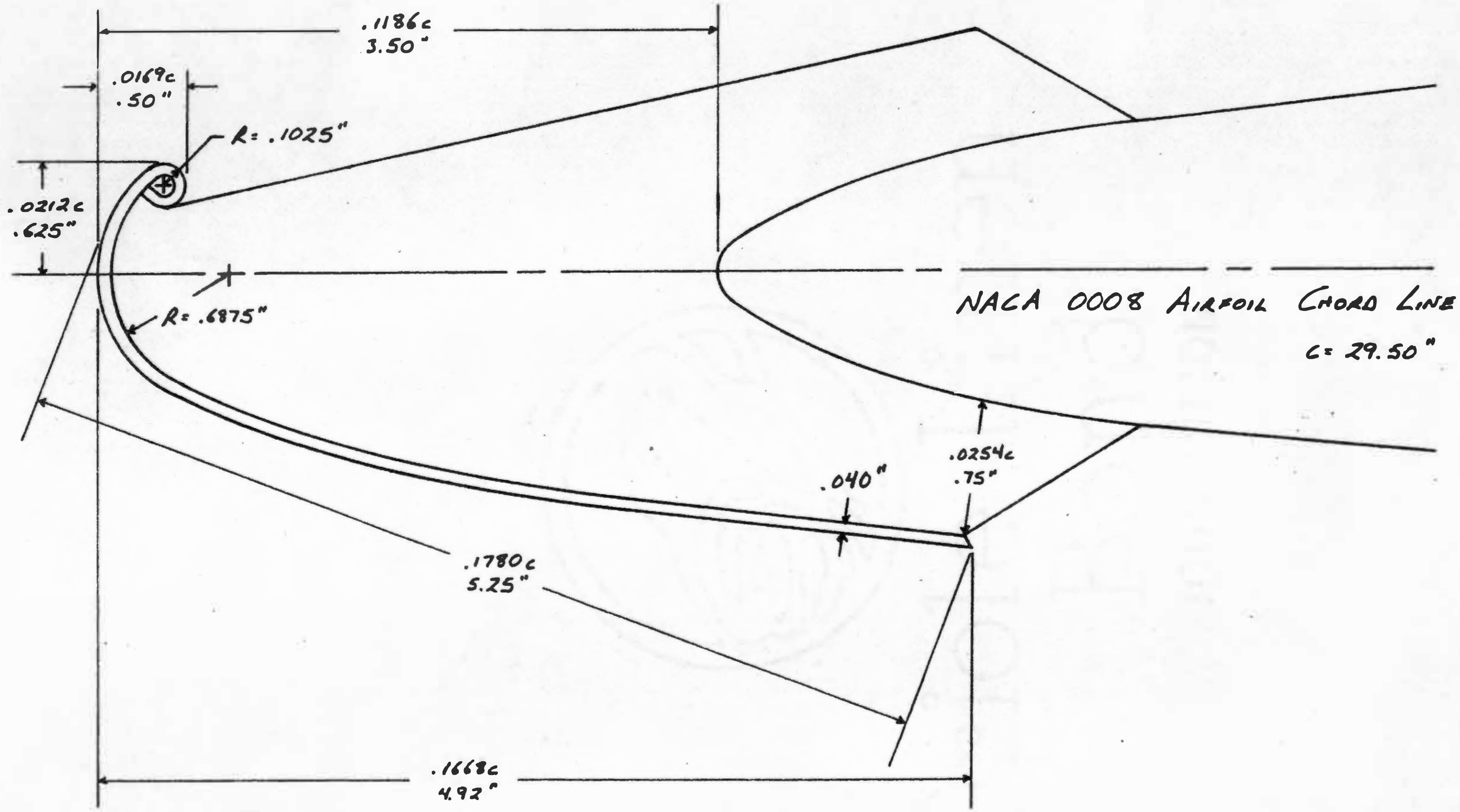


Figure 21. Proposed Thin Slat Design at the Minimum Chord Position

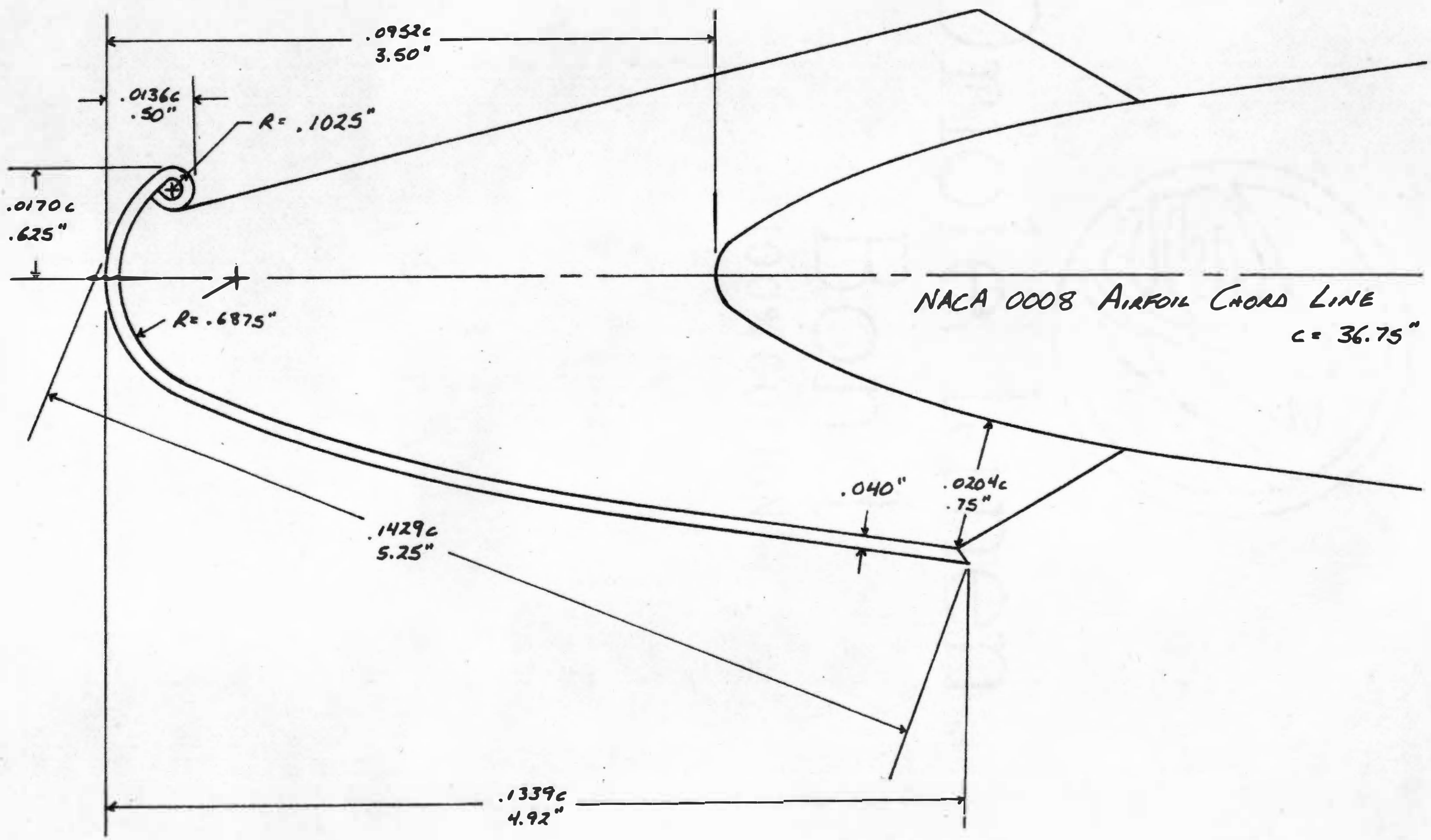


Figure 22. Proposed Thin Slat Design at the Mean Chord Position

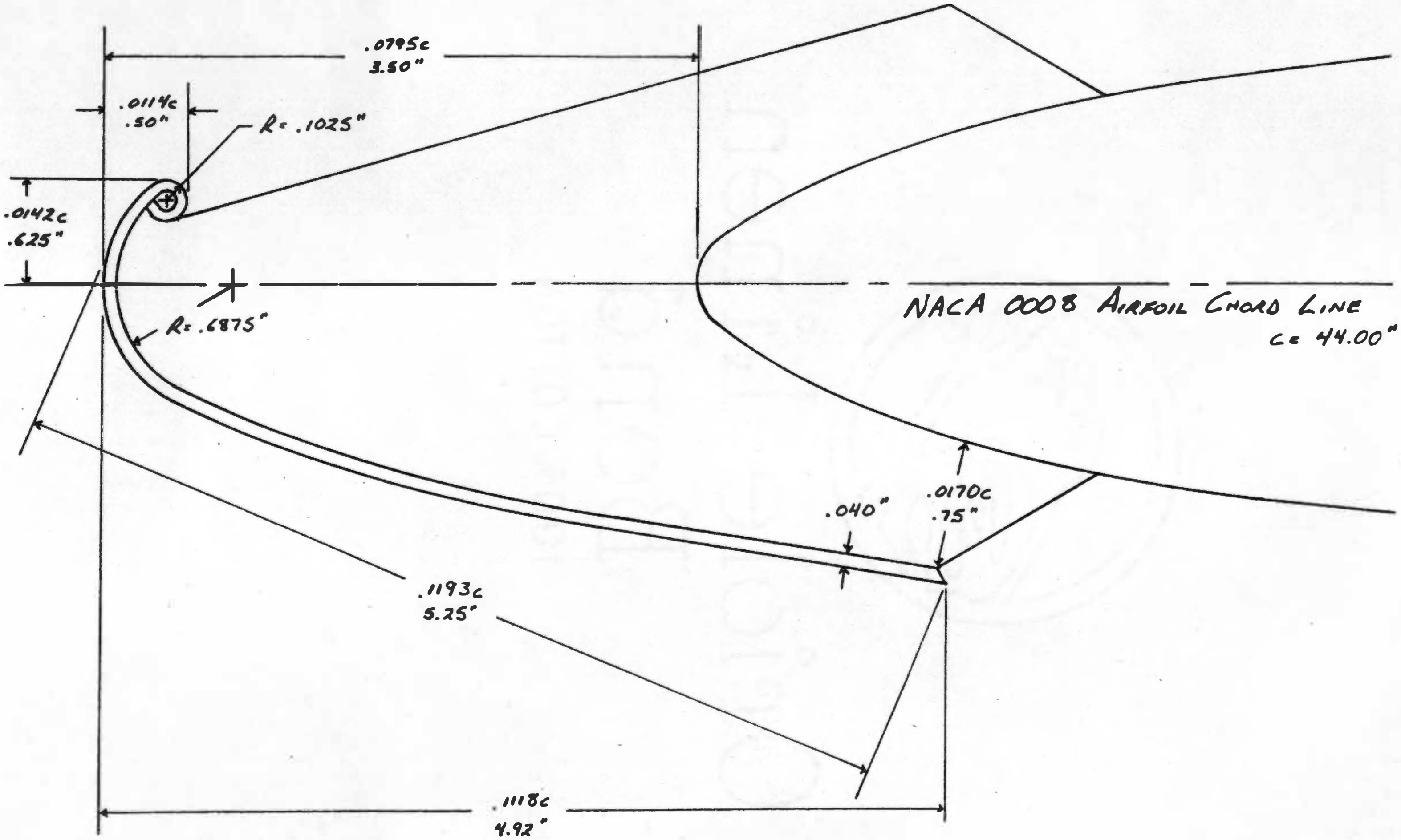


Figure 23. Proposed Thin Slat Design at the Maximum Chord Position

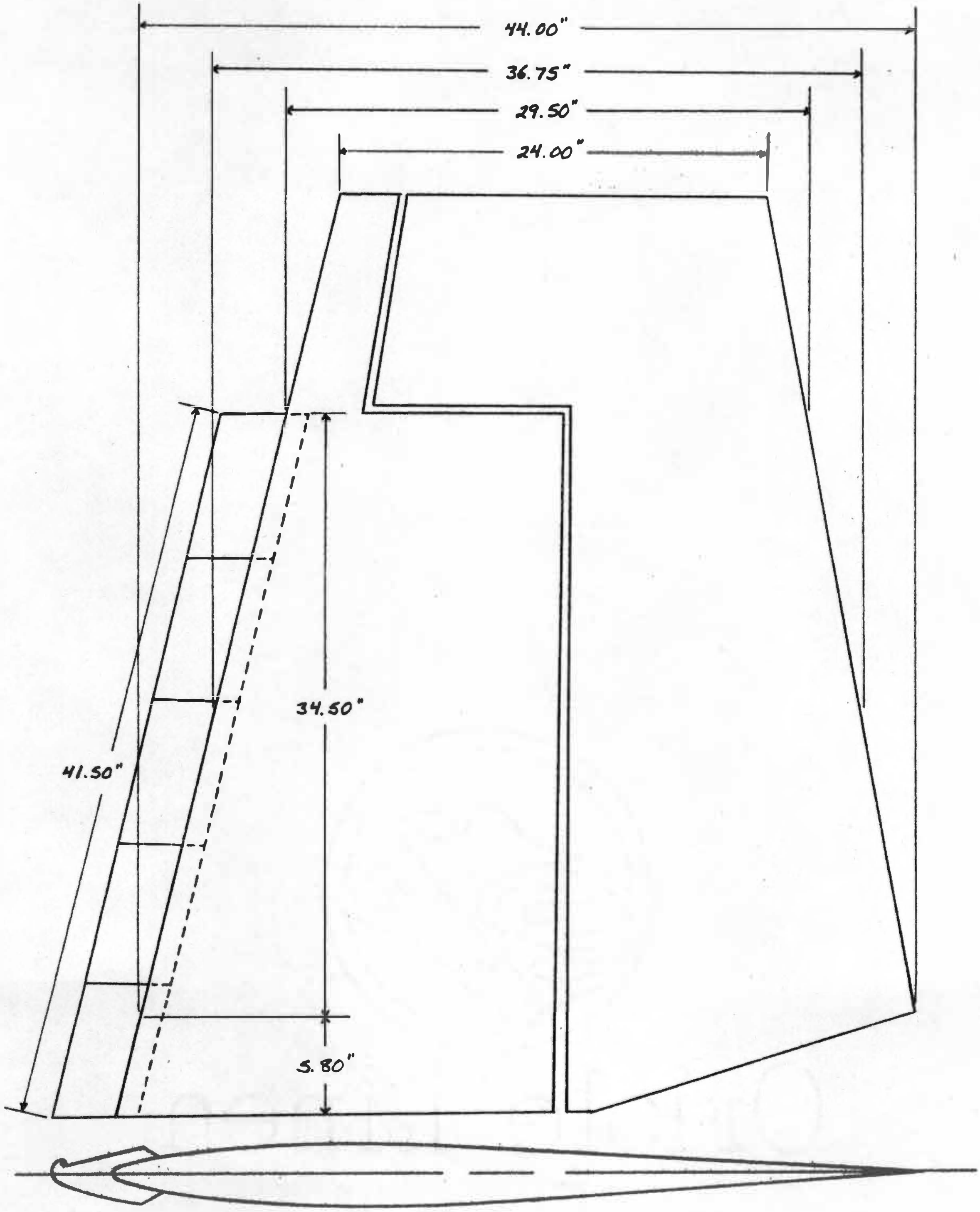


Figure 24. Planform View of the Horizontal Tail with the Proposed Modification

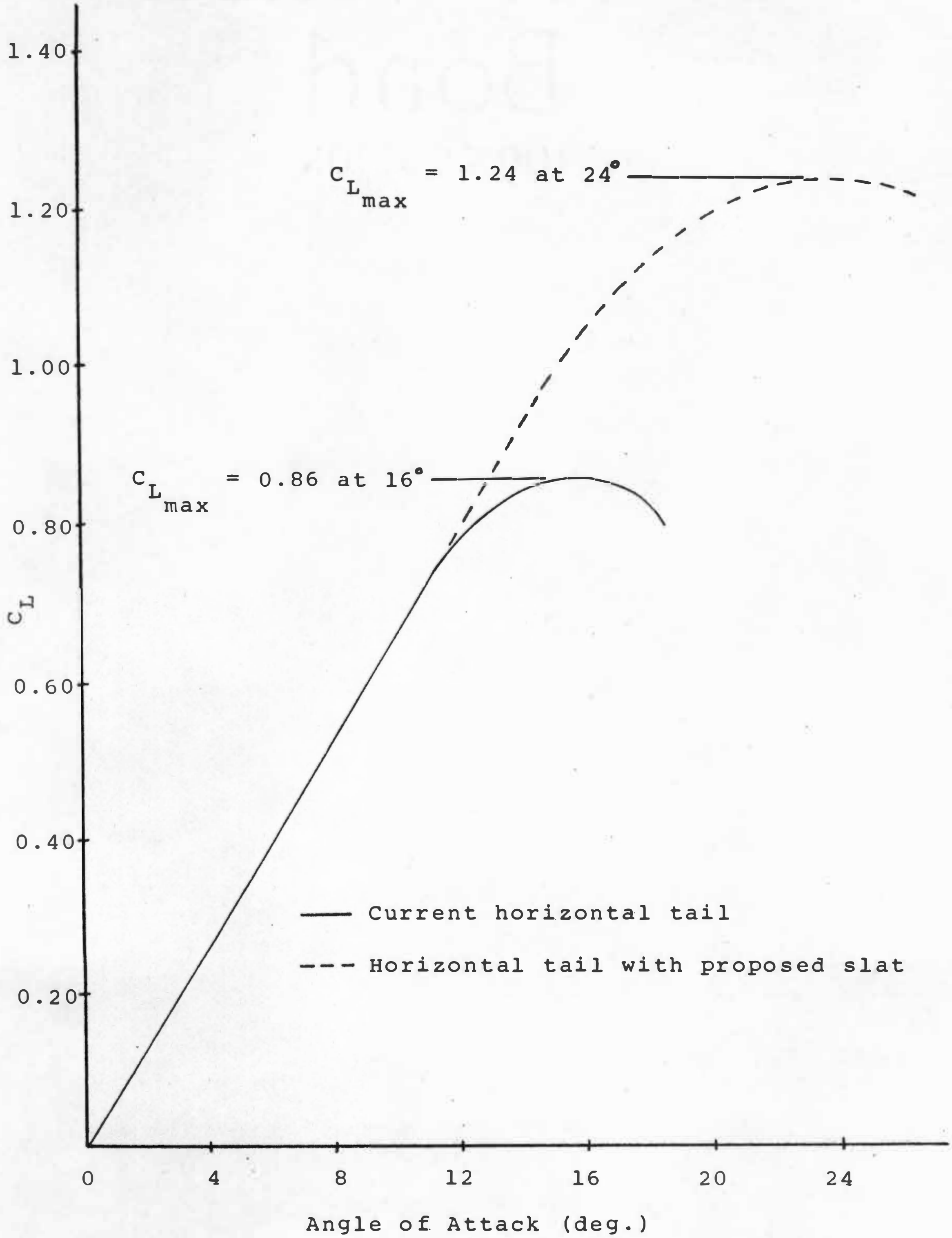
Fabrication and installation of the slat would be a simple and inexpensive task. The slat is constructed of 0.040 inch thick rolled aluminum sheeting which could be easily cut to the appropriate shape and would provide a sufficiently rigid surface when installed. The sheet would be crimped about a 0.125 inch diameter rod and then shaped about a constant radius form of 0.6875 inch to produce the leading edge. The remainder of the slat is a gentle flexure with a 45 degree bevel at the trailing edge. Each slat is attached to the tail surface by six stiffeners, also cut from 0.040 inch thick aluminium sheet metal. The total weight of the slats, stiffeners, and mounting hardware should be less than 4.0 pounds. The number and positions of the stiffeners are matched to the ribs in the horizontal tail in order that substantial structural support would be available. The rivets connecting the stiffeners to the tail should be placed through the existing rivet holes attaching the skin to the ribs to avoid weakening the structure of the leading edge and to save weight.

4.3. Projected Results

The installation of the proposed slat on the horizontal tail of the Ball-Bartoe Jetwing should resolve the longitudinal instabilities through an improvement in the aerodynamic characteristics of the tail. The three-dimensional lift coefficient of the tail surface was determined for the angle of attack range at a Reynolds number of 1.5 million. This condition is representative of the low airspeed regime in which the horizontal tail stall has been experienced. The lift slope was corrected for the finite span and compressibility effects, as defined by Leland M. Nicolai.[16] The maximum lift coefficient and stall angle were determined using Nicolai's methods for both the high and low aspect ratio surfaces, since the tail geometry was determined to fall within the border region between the two methods. The results of the two procedures compared reasonably well, with a 10 percent disagreement in the maximum lift coefficient and a 5 percent disagreement in the stall angle. The borderline geometry of the tail surface and the low airspeed condition were the primary sources of the uncertainty, due to the requirements of the methodology. In this situation, the high aspect ratio method was deemed to be more precise, and the analysis was continued with these results. The maximum coefficient of lift was determined to be 0.86 at a stall angle of 16 degrees.

No theoretical method exists for determining the incremental changes in the maximum lift coefficient and the stall angle for surfaces with leading edge devices.[16] Therefore, the effect of the proposed slat was derived from an analysis of the available experimental data. Optimization of the earliest fixed slat designs, using the slat shape cut from the leading edge of the airfoil, produced an increase in the maximum lift coefficient of about 40 percent. An increase in the maximum lift angle of 300 percent was achieved, although the slat designed for that configuration was not very useful at other conditions. An 87 percent increase in the maximum lift angle was found for the more reasonable optimized slat.[14] The application of contoured slats to reduce the drag rise produced increases of 35 percent in the maximum lift coefficient, 60 percent in the maximum lift angle, and 53 percent in the minimum drag coefficient.[12] The use of the thin slats designed by Bergey increased the maximum lift coefficient by 50 percent and the maximum lift angle by 65 percent.[15] The application of the thin slat to a real aircraft also produced the unexpected result of greatly reducing the flow separation at the joint between the wing and the fuselage. Although no data is available on the lift characteristics of thin airfoils fitted with fixed slats, the results could be expected to be similar since such uniform improvements have been achieved with a variety of airfoil shapes.

If the proposed slat improves the lift behavior of the NACA 0008 airfoil as well as the historical data indicated, the maximum lift coefficient would be boosted by 45 percent, from 0.86 to 1.24 and the maximum lift angle should increase by 50 percent, from 16 to 24 degrees, for a Reynolds Number of 1.5 million, as shown in Figure 25. The delay of the stall angle for an additional 8.0 degrees angle of attack



1.40
1.20
1.00
0.80
0.60
0.40
0.20
C_L
$C_{L_{max}}$ = 1.24 at 24°
$C_{L_{max}}$ = 0.86 at 16°
Current horizontal tail
Horizontal tail with proposed slat
0
4
8
12
16
20
24
Angle of Attack (deg.)

should provide some measure of stall resistance to the horizontal tail. The increased lift generated by the slat should also increase the tail effectiveness. Together, these improvements to the aerodynamic characteristics of the horizontal tail of the Jetwing should reduce the longitudinal instabilities caused by the severe down wash flow field created by large flap deflections under high power settings at low airspeed.

4.4. Recommendations

Two series of tests should be performed to determine the accuracy of these predicted improvements in the lift characteristics of the horizontal tail surface of the Ball-Bartoe Jetwing. First, a model of the horizontal tail should be tested with the proposed slat installed to determine the actual magnitude of the expected increases in the maximum lift coefficient and lift angle. The test program should also investigate the resulting additional drag, the applied aerodynamic loads on the slat structure, and the behavior of the surface in negative incident flow situations. The possibility that a more complex slat, one which is not designed for ease of fabrication and installation, might produce better results should also be considered and tested if the proposed slat does not perform as well as expected. Second, a deeper study of the flow field about the horizontal tail of the Jetwing should be conducted. The present data is very limited and, due to the inherent danger, is most limited for the configurations which create the greatest concern. If this data could be obtained, a clearer image of the requirements for the tail improvements would be available and might, perhaps, indicate that another approach to the solution would be more appropriate. The goal to be reached through the modification of the horizontal tail of the Ball-Bartoe Jetwing is the capability to explore the full potential of this unique aircraft.

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VITA

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